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Energy Storage Opportunities Analysis Phase II Final Report A Study for the DOE Energy Storage Systems Program

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A Study for the DOE Energy Storage Systems Program

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Abstract

This study on the opportunities for energy storage technologies determined electric utility application requirements, assessed the suitability of a variety of storage technologies to meet the requirements, and reviewed the compatibility of technologies to satisfy multiple applications in individual installations. The study is called "Opportunities Analysis" because it identified the most promising opportunities for the implementation of energy storage technologies in stationary applications. The study was sponsored by the U.S. DOE Energy Storage Systems Program through Sandia National Laboratories and was performed in coordination with industry experts from utilities, manufacturers, and research organizations. This Phase II report updates the Phase I analysis performed in 1994.

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Contents

Executive Summary	9
1. Introduction.....	9
1.1 The DOE Energy Storage Systems Program in the Context of Utility Restructuring and Distributed Power	9
1.2 Phase II Opportunities Analysis Objectives.....	10
2. Electric Power Applications of Energy Storage	11
2.1 Applications Definitions	11
2.2 Applications Technical Requirements.....	11
3. Technology for Electric Power Applications	13
3.1 Energy Storage Technologies	13
3.2 Non-Storage Technology and Non-Technology Options	17
3.3 Energy Storage Technology Compatibility with Individual Applications	17
4. Necessary Future Work	25
4.1 Cost Breakdowns for Comparison of Storage Systems to Alternatives.....	25
4.2 Markets and Benefits of Energy Storage in the Competitive U.S. Electricity Industry.....	26
4.3 Multiple Applications to Increase Benefits of a Single Energy Storage System.....	26
Appendix A. Technical Approach for the Phase II Analysis	27
Appendix B. Organizations Participating in the Phase II Opportunities Analysis	28
Appendix C. Fact Sheets for Ten Electric Power Applications of Energy Storage	34
Appendix D. Revisions to the Phase-I Cost-Breakdown Structure.....	54
Appendix E. Resources for Revision of Markets and Benefits Estimates.....	58

Figures

Figure 1. The AC Battery Installed at Brockway Standard's Lithography Plant in Homerville, GA.....	15
Figure 2. Electrochemical Capacitors	16
Figure 3. Carbon-fiber and Resin Composite Flywheel Rotor.....	16
Figure 4. Intermagnetics General Corporation's Truckable SMES and the Superconducting Magnet.....	17
Figure 5. Traditional coal-fired power plant	19
Figure 6. Schematic of a combustion gas turbine for electric power.....	19
Figure 7. Diesel generators manufactured by Caterpillar for 60-Hz electric power applications	19
Figure 8. Microturbines manufactured by Capstone Turbine Corporation use natural gas or biofuels and drive high speed electrical generators	19
Figure 9. Real-time transactions to buy and sell power provides electric power producers and service providers a way of addressing competitive needs.....	20
Figure 10. Peaking gas combustion turbine at Texas Utilities.....	20
Figure 11. FACTS depends on Westinghouse's solid-state STATCOM Switching Device to redirect power to under-utilized pathways.....	20
Figure 12. Recycling and energy recovery pilot plant (cogeneration) in California uses anaerobic composting to produce fuel gas that is dried and burned in an internal combustion engine to make electricity; extra gas fuels heaters, dryers, and steam boilers.....	21
Figure 13. Substation auto transformers like this one by Waukesha Electric Systems can manipulate taps to respond to 10 – 100 MVA transients	21
Figure 14. Distribution class capacitor banks made by Cooper Power Systems are typical of the parallel, series-parallel, or in a three-phase arrangement, 100, 150, and 200 kVar power ratings and 2,400 - to 21,600 - volt capacity.....	21
Figure 15. Oil coolers for transformers like this Seimens model help keep temperatures down even during peak loading – as a result, transformers can support larger loads for longer times before overheating.....	22
Figure 16. 100-foot, 12.5 kV, 1,250A underground transmission cable developed and demonstrated by Intermagnetics General Corporation, Southwire Company, and the US DOE was installed as a high-temperature (4K) superconducting cable.....	22
Figure 17. Fermilab's 1400-ton high-efficiency chiller.....	22
Figure 18. Static Interruptible Power Supplies (UPSs) like Exide Electronics' One UPS Plus can deliver hundreds of volt-amperes to ride through momentary service fluctuations and outages.....	23
Figure 19. Piller's Uniblock II rotary UPS combines digital control and power electronics with a rotating mass that provides inertia to drive a motor/generator for ride-through of momentary service fluctuations.....	23
Figure 20. Seimen's SIPCON – DVR (dynamic voltage restorers) shown here in a turn-key, semi-trailer container; these units located between distribution and load provide power (MVA) and energy (hundreds of kilojoules) to improve power quality	23

Figures (continued)

Figure C- 1.	System Need for Rapid Reserve Power.....	35
Figure C- 2.	Storage Response to Provide Rapid Reserve Power.....	35
Figure C- 3.	System Need for Area Control and Frequency Responsive Reserve	36
Figure C- 4.	Storage Response to Provide Area Control or Frequency Responsive Reserve ..	37
Figure C- 5.	Effect of storage used for Area Control or Frequency Responsive Reserve on utility grid load.....	37
Figure C- 6.	Typical Load Profile for an Aggregation of Customers - Peak has Potential to Approach Capacity as Load Grows	38
Figure C- 7.	Energy Storage Response to Commodity Storage Application Demands	38
Figure C- 8.	Utility System Needs to Address Transients and Achieve Stability	40
Figure C- 9.	Storage Response to Address Transients	41
Figure C- 10.	System Need for VARs to Correct Voltage Loss Due to Impedance.....	42
Figure C- 11.	Storage Injecting and Absorbing VARs During Discharge, Charge and Idle.....	42
Figure C- 12.	Load Exceeds Acceptable Percentage of Transmission Capacity	44
Figure C- 13.	Transmission Load Grows to Meet Demand	45
Figure C- 14.	Storage Response to Increase Transmission Capacity Until New Facilities are Cost-justified	45
Figure C- 15.	Distribution Load Exceeds Acceptable Percentage of Capacity	46
Figure C- 16.	Distribution Load Growth Approaches Capacity	46
Figure C- 17.	Storage Provides Peak Power to Temporarily Defer Purchase of New Equipment Until it is Cost-justified	47
Figure C- 18.	Customer Demand that Creates Economic Need to Reduce Peaks	48
Figure C- 19.	Energy Storage Providing Power to Manage Customer Load Profile	48
Figure C- 20.	Aggregate Load Peaks During a Typical Week that do not Coincide with Renewable Production Peaks	50
Figure C- 21.	Off-peak Storage of Renewable Energy for On-peak Dispatch to Increase Capacity Credit and Economic Value of Renewables	51
Figure C- 22.	A 50-volt Transient Spike on a 480-Volt Line that Could Cause an Outage at a Production Facility.....	53
Figure C- 23.	Storage Delivers and Absorbs Power Fluctuations as Needed	53

Tables

Table 1.	Definitions and Categories of Electric Power Applications of Energy Storage	12
Table 2.	Summary of Applications Requirements	14
Table 3.	Non-Storage Technology and Non-Technology Options for Electric Power Applications	18
Table 4.	Technical and Strategic Advantages and Disadvantages of Non-Storage Technology and Non-Technology Options	19
Table 5.	Functional Capabilities of Storage Technologies for Electric Power Applications.	24
Table D-1.	Cost Components for an Energy Storage System.....	57

Acronyms and Abbreviations

APS	Advanced Pumped Storage
ASTM	American Society For Testing and Materials
CAES	Compressed Air Energy Storage
CAS	Compressed Air Storage
DOE	Department of Energy
ECs	Electrochemical Capacitors
ESS	Energy Storage Systems
FACTS	Flexible Alternating Current Transmission System
FES	Flywheel Energy Storage
HTS	High Temperature Superconductivity
PCS	Power Conversion System
R&D	Research And Development
SMES	Superconducting Magnetic Energy Storage
SNL	Sandia National Laboratories
T&D	Transmission And Distribution
VAR	Volt-Amp Reactive
VRLA	Valve-Regulated Lead-Acid

Energy Storage Opportunities Analysis Phase II Final Report

A Study for the DOE Energy Storage Systems Program

Executive Summary

The Opportunities Analysis was intended to characterize the potential for providing energy storage options to provide significant benefits to electric utilities and their customers. This study, the Phase II – Opportunities Analysis expands on the Phase I study in defining the potential application requirements, preliminary benefits and costs of energy storage. Uncertainty resulting from electric power industry changes was considered and a broad array of technical experts participated in the analysis.

This Phase II study updates and enhances several aspects of the earlier Phase I Opportunities Analysis report published in 1994. The Phase II study includes definitions and characteristics of utility applications for energy storage and fact sheets for each application. The Phase II study participants concluded that ten of the original thirteen feasible applications of energy storage systems are in general demand and have high value for electric power producers and their customers. Power and energy requirements were identified and a duty cycle was defined for each application. This study expanded the scope from Phase I to include emerging non-battery technologies to serve utility applications. Three categories of energy storage technologies are addressed in this report:

- Electrochemical storage devices including flooded and valve-regulated lead-acid batteries, lithium/polymer batteries, nickel/metal hydride batteries, sodium/sulfur batteries, vanadium-redox batteries, zinc/bromine batteries, and electrochemical capacitors
- Electromechanical storage devices including steel and composite rotor flywheels
- Electrical storage devices such as superconducting magnetic energy storage (SMES).

Four important conclusions regarding energy storage technologies can be gained from this study:

- The lead-acid battery technologies have the most field experience and can adequately satisfy most of the defined utility energy storage applications. However, if footprint and portability are important, then lead-acid batteries may not be an ideal energy storage solution
- The remaining electrochemical storage devices (sodium/sulfur, nickel/metal hydride, lithium/polymer, vanadium-redox and zinc/bromide batteries and electrochemical capacitors) are considered potential candidates for all applications, however, some of these technologies are just emerging as pilot-scale systems and have not been fully evaluated
- Steel rotor FES has limited promise for the entire array of applications but is well-suited to hybrid FES/battery power quality applications. Composite-rotor FES has potential for broader applicability but will require significant development to compete with other, more mature technologies and non-technology options.
- SMES has the potential to provide electrical storage to a majority of the applications. However, this technology is still emerging, and more R&D will be needed to make SMES competitive in a wide variety of utility storage markets.

This Phase II report provides a more updated framework for evaluating energy storage in utility applications.

1. Introduction

1.1 The DOE Energy Storage Systems Program in the Context of Utility Restructuring and Distributed Power

The U.S Department of Energy (DOE) Energy Storage Systems (ESS) Program at Sandia National Laboratories (SNL) is responsible for the development of hardware (storage components, power electronics, control systems, system integration components and system testing) and communication to stakeholders of the status and benefits of storage systems in specific applications. As the

electric power industry in the U.S. is changing, the ESS Program is responding by conducting research and development (R&D) and analyses that help to increase the reliability and economic value of electricity production in the U.S. while also helping to make it more environmentally sustainable.

In the last three decades, the electric power industry has changed significantly. In the 1970s the nation's electric power industry consisted of regulated, vertically-integrated companies that generated, transmitted and distributed electricity under terms established by Federal and State agencies. In general, electric power producers owned and operated large power plants with hundreds of megawatts of generating capacity, transmission lines that carried power over long distances and distribution lines that served communities and individual customers that existed far from the large central generating station. This approach to making and delivering electric power took advantage of economies of scale that were available in a regulated business environment and possible with the technology of the era. However, the 1980s and '90s brought with them a series of legislative acts and technological advances that reduced the value of a vertically-integrated business structure and the economy of scale of large, central power stations.

Regulators ratified rules that increased competition and electric power producers began to separate their generation, transmission and distribution and customer service operations into discrete business units. One likely outcome of this industry restructuring is that all electricity consumers will be able to choose their power provider much like telephone account holders now choose their long-distance service providers. As of June 2001, twenty-four states and the District of Columbia have enacted comprehensive electricity restructuring legislation or regulatory orders.

In this competitive environment, smaller, distributed power generation and delivery have increased in value and new companies that provide energy services have emerged to serve the changing market place. Coupled with the new economic viability of smaller distributed power facilities, technical advances have made new technologies available to serve distributed power applications. Among these technologies that compliment and compete with traditional electric power technologies are more efficient diesel and gas generators, microturbines, fuel cells, fast switches, sophisticated on-site and remote controls and turn-key energy storage systems that include electrochemical batteries, electromechanical systems (flywheels) and direct current (DC) storage devices.

In response to the changes in the U.S. electric power industry, the ESS Program has helped to identify the applications that energy storage can best serve,

conducted R&D on technologies for those applications and transferred technology to power equipment manufacturers and power producers. As part of this process to ensure that the nation has access to the most economically and environmentally sustainable power technologies available, the ESS Program initiated an Opportunities Analysis for energy storage in 1993. This analysis had the goal of developing improved understanding of electric-power applications' requirements, battery systems' capabilities and the benefits possible from serving applications with battery storage.

Even as SNL prepared the report for the Opportunities Analysis for publication in 1994, participants recognized that dramatic changes in the electric power industry and improvements in emerging technologies would make updates to the results necessary. In recognition of this need, the title to that report identified the project as Phase I of an analysis that would be part of a continuing body of work.¹ As expected, the applications and the technologies to serve them changed. In 1998, the ESS Program initiated Phase II of the Opportunities Analysis to expand the scope of the study to include a wider range of energy storage technologies and to address the effects of restructuring on the applications' requirements. SNL pursued an approach for the Phase II analysis similar to the Phase I approach which consisted of working meetings with stakeholders in the electric power industry and post-meeting research and analysis. Appendix A presents the details of the approach. Appendix B presents the names and roles of the industry stakeholders that participated in the working meetings. The following section details the objectives of the Phase II Opportunities Analysis.

1.2 Phase II Opportunities Analysis Objectives

The Phase I analysis identified 13 applications of battery energy storage systems and three sets of combined applications that a single energy storage system could serve to achieve better benefit/cost ratios. The report also discussed the best-fit combinations of specific technologies with applications and combinations of applications. The Phase I document presented the first attempt to break

¹ Battery Energy Storage for Utility Applications: Phase I – Opportunities Analysis, P. Butler, SAND94-2605, 1994.

down the cost components of an energy storage system so that direct benefit/cost assessment against traditional technologies was possible. The report also made the first attempt to quantify the markets for energy storage systems in electric power applications and estimate the benefits to the nation of energy storage penetrating those markets.

As a follow-on to the Phase I work, the Phase II effort had the following original objectives:

1. Reassess the value of applications for energy storage in a competitive electric power industry
2. Refine definitions of application requirements for energy storage systems
3. Identify the best applications of specific energy storage system technologies
4. Reassess the potential market size and benefits of energy storage
5. Refine the previously defined cost breakdown for energy storage systems to allow comparison of storage systems and other technologies for electric power applications.

While analysts pursued the first three objectives, they also identified significant barriers to achieving the fourth and fifth objectives of the Phase II work. As a result, objectives four and five were deferred for later analysis that would be founded on more substantial data than were available at the time of the Phase II work. Section 4 of this report presents a discussion of the necessary future work in markets and benefits assessment and refinements of cost breakdowns.

2. Electric Power Applications of Energy Storage

2.1 Applications Definitions

The group of industry experts who participated in the Phase II project used the perceived need for each application across the nation and the potential technical and economic benefits for utilities as criteria to evaluate the 13 applications identified in the Phase I report and other potential applications. From this process emerged the definitions shown in Table 1 for ten individual applications of energy storage that are in general demand and have high value for electric power producers and their customers. Table 1 also shows an organization of the applications under headings of Generation, Transmission and Distribution (T&D) and Customer Service. Although utility functions of generation,

transmission and distribution and customer service now generally occur in separate business units, the organization for the applications under those headings does not signify that a storage system could/should serve only one application or application type. In fact, as discussed in Section 4.2 of this report, a storage system is most valuable to a utility when it performs multiple functions in more than one of these groups of applications.

2.2 Applications Technical Requirements

Regulatory, operational and economic influences create technical requirements for each electric power application of energy storage. The industry experts who participated in this effort identified the application requirements shown below as the most significant to electric power applications: power, duration of discharge, AC system voltage, floor-space requirements, portability, and the type, number and distribution of duty cycles. The characteristics of the operating environment are also important for technical requirements for an energy storage system. Table 2 summarizes the requirements of energy storage systems for the ten candidate utility applications.

Power Requirements

Kilo/mega-watts (kW or MW) for real power, kilo/mega-vars (kVAR or MVAR) for reactive power, kilo/mega-volt-amperes (kVA or MVA) for a combination of real and reactive power

Power requirements determine the size of the power conversion system and can influence the capacity of the system via the power-to-energy ratio. An energy storage system must be rated so that power drain does not significantly reduce its cycle life. Power requirements impact the size and cost of the energy storage system, the support structure and the building. High power levels increase the cost of the control and power-handling equipment. Electric arc furnaces, cranes, welding machines, rolling mills and other induction motors typically have large and/or widely fluctuating needs for reactive power that can cause production or operational disturbances and reduce the life of the manufacturing equipment. Utilities experience higher impedance and reduced capacity on transmission and distribution lines with reactive loading. Therefore power providers typically impose a kVA demand charge to compensate for this cost. To avoid this charge, industrial facilities often try to supply reactive power onsite using generators, capacitors, synchronous motors and other technologies.

Table 1. Definitions and Categories of Electric Power Applications of Energy Storage

Category	Application Name and Definition
Generation	Rapid Reserve Generation capacity that a utility holds in reserve to meet North American Electric Reliability Council (NERC) Policy 10* requirements to prevent interruption of service to customers in the event of a failure of an operating generating station.
	Area Control and Frequency Responsive Reserve The ability for grid-connected utilities to prevent unplanned transfer of power between themselves and neighboring utilities (Area Control) and the ability of isolated utilities to instantaneously respond to frequency deviations (Frequency Responsive Reserve). Both applications stem from NERC Policy 10 requirements.
	Commodity Storage Storage of inexpensive off-peak power for dispatch during relatively expensive on-peak hours. In this report, Commodity Storage refers to applications that require less than four hours of storage.
Transmission & Distribution	Transmission System Stability Ability to keep all components on a transmission line in sync with each other and prevent system collapse.
	Transmission Voltage Regulation Ability to maintain the voltages at the generation and load ends of a transmission line within five percent of each other.
	Transmission Facility Deferral Ability of a utility to postpone installation of new transmission lines and transformers by supplementing the existing facilities with another resource.
	Distribution Facility Deferral Ability of a utility to postpone installation of new distribution lines and transformers by supplementing the existing facilities with another resource.
Customer Service	Customer Energy Management Dispatching energy stored during off-peak or low cost times to manage demand on utility-sourced power.
	Renewable Energy Management Applications through which renewable power is available during peak utility demand (coincident peak) and available at a consistent level.
	Power Quality and Reliability Ability to prevent voltage spikes, voltage sags, and power outages that last for a few cycles (less than one second) to minutes from causing data and production loss for customers.

* (available for download at <http://www.nerc.com/~oc/>)

Duration of Discharge/Energy Requirements

Time units (sec, min, hr) for duration of discharge and kilo- or mega-watt-hours (kWh or MWh) for energy required

Energy is the amount of power delivered over a period of time. Therefore, the longer the discharge duration at any power, the greater the energy that the storage system must be able to deliver. Energy requirements typically determine the size of the system. Consideration must be given to the effect of discharge depth on the service life of the system. Higher energy requirements result in increases in the size and cost of the shelter and support structure.

AC System Voltage Requirements

Root-mean square of the load in kilovolts (kV_{RMS})

The AC system voltage and maximum current demand determine the size and the cost of the transformer between the power conditioning system and the AC source and load. Voltage requirements also influence the gauge and cost of cabling for the system.

Floor Space/Footprint Requirements

Square feet of area (ft^2) that the energy storage system occupies

As implied above, the application requirements influence physical size and the physical size affects the cost of entire system. For many applications, and for some utilities, space availability is very significant in the selection and cost of a storage system.

Portability Requirements

Relative difficulty or cost of transporting the energy storage system to either temporary or permanent sites

Some applications are temporary in nature, therefore the ability to transfer a storage system from site to site can significantly increase its overall value. Portability varies greatly between types of systems. Superconducting magnetic energy storage (SMES) units, battery storage systems and flywheel energy storage systems are all now offered commercially as pre-packaged, turn-key systems that fit into containers with all necessary monitors, controls and power conditioning equipment for easy transportation and installation. For large systems requiring significant energy content, however, portable systems may not be feasible, as the size of the storage media often becomes impractical or non-economic for transport.

Duty Cycle Requirements

Quantity and periodicity (uniformly distributed, vs. clustered and predictable vs. random) of discharge over a specified time period

The characteristics of the duty cycle affect the performance and service life of the storage device. Cycling requirements influence the size and change-out interval for both the storage media and peripheral components. The nature of the duty cycle profile, its distribution and frequency also affect the efficiency of virtually all storage systems. While frequent cycles increase the efficiency of some storage media, they decrease efficiency of others. Frequent cycling also introduces transient effects and associated system inefficiencies that can increase cycle life cost, increase the necessary size of the storage or power electronics and, therefore, the cost of the system.

3. Technology for Electric Power Applications

3.1 Energy Storage Technologies

Analysts established criteria to choose technologies that were both advanced enough in their development to be viable candidates for the storage applications under consideration, but that still required additional systems or component development for full market penetration. Based upon these two criteria, the following storage technologies were chosen for inclusion in this report: lead-acid batteries, (flooded and valve-regulated), lithium/polymer batteries, nickel/metal hydride batteries, sodium/sulfur batteries, vanadium-redox batteries, zinc/bromine batteries, flywheels (steel and composite rotors), superconducting magnetic energy storage and electrochemical capacitors.

Table 2. Summary of Applications Requirements

Application	Power*	Storage (minutes)	AC Voltage (kV_{RMS})	Floor Space (importance)	Portability (importance)	Duty Cycle Requirements	Special Demands
Rapid Reserve	10^1 - 10^2 real	10^1 - 10^2	10^1 - 10^2	Medium	Low	10^1 /year, random, discharge only	None
Area Control & Frequency Responsive Reserve	10^1 - 10^2 real	Charge/discharge cycles of $<10^1$	10^1 - 10^2	Low	Low	Random, continuous charge/discharge cycles clustered in 2-hour blocks daily	None
Commodity Storage	10^0 - 10^2 real	10^2 - 10^3	10^1 - 10^3	Medium	Negligible	10^2 /year, regular, periodic, weekday block discharge, increased use in shoulder months	Harmonics are more important than in other generation applications
Transmission System Stability	10^1 - 10^2 complex	10^3 - 10^1	10^1 - 10^3	Medium	Low	10^2 /year, random, charge & discharge cycles	None
Transmission Voltage Regulation	10^0 - 10^1 reactive	10^1 - 10^2	10^1 - 10^2	Medium	High	10^2 /year, random charge & discharge cycles typically weekdays, seasonal by region – at least 6-7 months	Safety concerns are important
Transmission Facility Deferral	10^{-1} - 10^1 complex	10^2	10^1 - 10^2	High	High	10^2 /year, most likely during weekday peaks, charge & discharge	Safety concerns are important
Distribution Facility Deferral	10^{-1} - 10^0 real	10^2	10^0 - 10^1	High	High	10^2 /year, most likely during weekday peaks, charge & discharge	Safety concerns are important
Customer Energy Management	10^{-2} - 10^1 complex	10^1 - 10^2	10^{-1} - 10^1	High	Varies	10^2 - 10^3 /year, regular periods	Safety concerns are important
Renewable Energy Management	10^{-2} - 10^2 complex	10^{-3} - 10^3	Variable	High	High	10^2 - 10^3 /year, regular periods, discharge only, unpredictable source	Hostile environments including extreme heat and cold, particulates and corrosive atmospheres
Power Quality & Reliability	10^{-2} - 10^1 complex	10^{-3} - 10^0	10^{-1} - 10^1	High	Varies	10^2 - 10^3 /year, irregular periods, charge & discharge	Safety concerns are important

* Real (MW), Reactive (MVAR), or Complex (MVA)

Appendix C of this report contains fact sheets for each application identified above. The fact sheets discuss the applications in terms of their operational and economic significance in the electric power industry and the technical requirements they impose on energy storage systems. The fact sheets include graphical illustration of a load profile that creates the application, text description of the application and the rationale for storage. The fact sheets also present the power and energy requirements for the application, annual number of cycles that the system would experience and the expected distribution of cycles throughout the year.

Electrochemical Storage Systems

Electrochemical batteries are storage media in which reversible electrochemical reactions enable storage of electrical energy as chemical potential and release of that energy on demand. In general, electrical energy introduced into an electrochemical battery causes reactions that make one electrode lose electrons and the other electrode gain electrons. The potential energy is stored in the charged electrodes and they release it when they return to their uncharged states. Because these electrochemical reactions are not perfectly efficient, some of the energy is lost in both charging and discharging the battery. Each battery technology has its own unique set of electrochemical reactions, materials, and electrical characteristics. This wide variety of attributes leads to tremendous diversity in battery types and uses.



Figure 1. The AC Battery Installed at Brockway Standard's Lithography Plant in Homerville, GA.

To be useful in electric power applications described in this report, the battery must be part of a fully integrated system that includes sophisticated solid-

state power conversion devices, monitors, controls, climate controls, utility and user interface equipment, safety devices and transportation features. The technical challenges of integrating subsystems within a turn-key storage system are applicable to all technologies addressed in this chapter.

Electrochemical batteries considered in this study include the most technically mature and well understood electrochemistries and those just emerging for field demonstrations. The most mature technology, flooded lead-acid batteries and valve-regulated lead-acid (VRLA) batteries, have been in service in electric power applications such as those identified in this report for nearly two decades². Figure 1 shows a 10-second, 1 MW lead-acid battery energy storage system installed at a lithography plant to improve power quality by protecting the plant from surges, sags and momentary interruptions. Zinc/bromine, sodium/sulfur and vanadium-redox batteries also have some field experience in electric power applications³, but are at earlier stages of their technical maturity than lead-acid technologies. Lithium/polymer and nickel/metal hydride, also included in this study as candidate storage media, are just emerging in pilot scale systems that might serve some of the electric power applications identified in this report. Linden's battery handbook contains complete descriptions of the characteristics of the electrochemistries mentioned above⁴.

²Lessons Learned from the Puerto Rico Battery Energy Storage System, M. Farber DeAnda, et al., SAND99-2232, 1999; Final Report on the Development of a 250kW Modular, Factory-Assembled BESS, Corey, et al., SAND97-1226, 1997; Final Report on the Development of a 2 MW/10 Second Battery Energy Storage System to Power Disturbance Protection, Omnion, #DE-FC04-94AL99852.

³ Development of Zinc/Bromine Batteries for Load-leveling Applications; Phase II Final Report, SAND89-2691, 1989.

⁴ *Handbook of Batteries 2nd Edition*, D. Linden ed., McGraw-Hill Book Company; New York. 1994.

Electrochemical capacitors, or ECs, are the major new capacitor technology to emerge in the last 15 years. An electrochemical capacitor can be thought of as part battery and part capacitor. Electrochemical capacitors are also known under a variety of other names and trademarks including supercap, ultracapacitor, double-layer capacitor, etc. In the simplest terms, electrochemical capacitors resemble batteries because the charge is stored by ions and resemble capacitors because no chemical reaction is involved in energy delivery. However, under certain



Figure 2. Electrochemical Capacitors

conditions, called pseudocapacitance, chemical reactions do occur within the capacitor and serve to increase the capacitor's energy density.

Electrochemical capacitors exhibit much greater energy densities compared to traditional capacitors due to the use of extremely high surface area electrodes which store charge in an ionic double layer near the electrodes' surfaces. Figure 2 shows electrochemical capacitors under development by Maxwell Technologies.

Electromechanical Energy Storage Systems (Flywheel Systems)

In electromechanical systems, the kinetic energy of a moving mass stores electrical energy. The most prevalent type of mass in an electromechanical storage system is a rotating mass, or flywheel. Like electrochemical batteries, flywheels must be part of a fully integrated system that includes sophisticated solid-state power conversion devices, monitors, controls, climate controls, utility and user interface equipment, safety devices and transportation features to be useful in electric power applications described in this report.

Flywheel systems considered in this study include those with steel flywheel rotors and resin/glass or resin/carbon-fiber composite rotors. Figure 3 shows

a flywheel rotor (manufactured by Flywheel Energy Systems, Inc. of Ontario, Canada) for a flywheel system. The mechanics of energy storage in a flywheel system are common to both steel- and composite-rotor flywheels. In both systems, the momentum (the product of mass times velocity) of the moving rotor stores energy. In both types of systems, the rotor operates in a vacuum and spins on bearings to reduce friction and increase efficiency. The rotor, loaded with magnets, is effectively part of an electromagnetic motor/generator that converts energy between electrical and mechanical forms. Steel-rotor systems rely mostly on the mass of the rotor to store energy and composite flywheels rely mostly on speed.

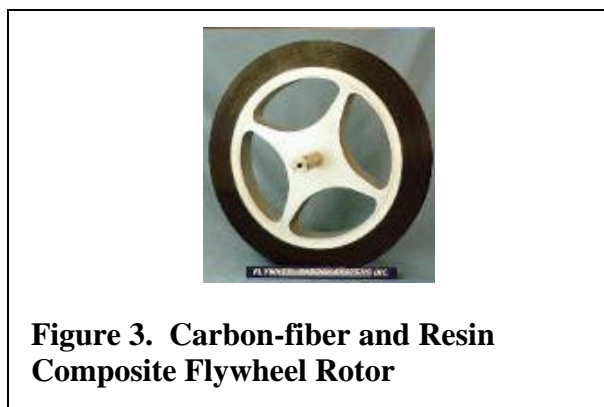


Figure 3. Carbon-fiber and Resin Composite Flywheel Rotor

During charging, an electric current flows through an electromagnetic coil and creates a magnetic field that interacts with the magnets loaded on the rotor, causing it to spin. During discharge, the spinning magnets on the rotor induce a current in the electromagnet and generate current flow out of the system. A report published by SNL for the ESS Program in 1999⁵ describes the attributes of each rotor type and the subsystems that make up a turn-key flywheel energy storage system.

Electrical Storage Devices

Electrical storage devices store electrical energy without conversion to chemical or mechanical forms. The electrical storage devices considered in this report is SMES.

In a SMES device, a coil of superconducting wire allows a direct electrical current to flow through it with virtually no loss. The current creates a magnetic field that stores the energy. On discharge, special

⁵ A Summary of the State of the Art of SMES, FES and CAES, Taylor, et al., SAND99-154, 1999.



Figure 4. Intermagnetics General Corporation's Truckable SMES and the Superconducting Magnet

switches tap the circulating current and release it to serve a load. To remain superconducting, the SMES coil must operate at cryogenic temperatures. Therefore, SMES devices require cryogenic refrigerators and related subsystems in addition to the solid-state power conversion devices, monitors, controls, climate controls, utility and user interface equipment, safety devices and transportation features that are necessary to be useful in electric power

applications described in this report. Figure 4 shows a fully integrated, turn-key SMES system mounted in a semi-trailer for transportability. A report published by SNL for the ESS Program in 1999⁴ describes the attributes of superconductors, cryogenics and other subsystems that make up a turn-key SMES system.

3.2 Non-Storage Technology and Non-Technology Options

Electric power providers and their customers have an arsenal of technologies at their disposal to serve the applications identified in this report. To supplement or replace traditional and emerging technology options, energy storage technologies will have to offer superior performance and lower cost than the more traditional technologies. Technology options may have to supplement non-technology options, such as spot purchases, for power providers and their customers to choose them in a competitive electric power industry. Table 3 presents the non-storage technology and non-technology options that energy storage will have to supplement or replace for each of the ten electric power applications. Table 4 describes these non-storage technology and non-technology options and lists some of the advantages and disadvantages for each.

3.3 Energy Storage Technology Compatibility with Individual Applications

The technical attributes of the various storage technologies considered in this report are compatible

with some electric power applications and incompatible with others. Table 5 presents the compatibility between applications and storage technologies agreed upon by participants in this study. The compatibility ratings consider the following information:

- the technologies' capabilities in the near- and mid-terms (as presented by participants in this study who develop the technologies)
- the information in the preceding descriptions of the storage technologies
- technical and non-technical alternatives
- the applications' requirements presented in preceding tables and in Appendix C of this report.

Table 5 does not address the disparate state of the development and experience of the storage technologies, nor does it treat the cost competitiveness of the technologies in the various applications. For example, flooded lead-acid and VRLA batteries have a D-rating (definite capability) for Area Control/Frequency Responsive Reserve while composite rotors for flywheels have an L-rating (likely capability). These ratings indicate that flooded lead-acid batteries can “definitely” serve the

application and that composite flywheels are “likely” to be able to serve the application in the future. These ratings are based on the fact that lead-acid technology has already successfully served the application and composite flywheel developers believe that their technology will. Therefore, the ratings do not reflect which technology will address the application requirements more cost effectively





when they are at the same level of technical maturity and experience.




Table 3. Non-Storage Technology and Non-Technology Options for Electric Power Applications



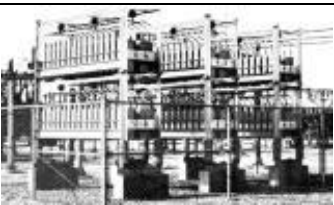
Application	Technology
Rapid Reserve	Centralized stations: backed-off thermal fossil, combustion gas turbines, small diesel generator systems, spot purchases (in the future competitive industry); Distributed units: diesel generators, microturbines
Area Control and Frequency Responsive Reserve	Intermediate cycling and peaking plants, combustion turbines
Commodity Storage	Flexible AC Transmission System (FACTS)*, Cogeneration
Transmission System Stability	Auto transformers, Flexible AC Transmission System (FACTS)
Transmission Voltage Regulation	Capacitor banks
Transmission Facility Deferral	Diesel generators, oil coolers for transformers, superconducting cables (future)
Distribution Facility Deferral	Diesel generators, oil coolers for transformers, superconducting cables (future)
Customer Energy Management	Thermal storage (passive solar, chiller), diesel generators, microturbines
Renewable Energy Management	Diesel generators
Power Quality and Reliability	Diesel generators, static uninterruptible power supplies (UPS), rotary UPS, dynamic voltage restorers

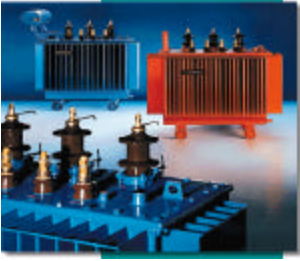


*While FACTS does not store energy for dispatch during peak times, the technology allows reconfigured dispatch of existing infrastructure and redirects surplus power around bottlenecks in transmission systems so that load peaks can be served. However, FACTS is only a partial solution for commodity storage because the arbitrage option is not available.

Table 4. Technical and Strategic Advantages and Disadvantages of Non-Storage Technology and Non-Technology Options

Option	Advantages	Disadvantages	Applications
 <p>Figure 5. Traditional coal-fired power plant</p>	<ul style="list-style-type: none"> Accepted industry practice Well-understood technology No initial capital cost for existing units 	<ul style="list-style-type: none"> High maintenance Inefficient Air emissions (SO_x, NO_x) Usually run in a backed-off mode 	<ul style="list-style-type: none"> Rapid Reserve
 <p>Figure 6. Schematic of a combustion gas turbine for electric power</p>	<ul style="list-style-type: none"> High degree of market acceptance Well-understood technology Relatively low cost (capital: \$400/kW, operating: \$0.02/kWh) 	<ul style="list-style-type: none"> High maintenance Air emissions (SO_x, NO_x) 	<ul style="list-style-type: none"> Rapid Reserve
 <p>Figure 7. Diesel generators manufactured by Caterpillar for 60-Hz electric power applications</p>	<ul style="list-style-type: none"> High degree of market acceptance Well understood technology Relatively low cost (capital: \$650/kW, operating: \$0.035/kWh) 	<ul style="list-style-type: none"> Air emissions (SO_x, NO_x) Varying fuel costs 	<ul style="list-style-type: none"> Rapid Reserve Transmission Facility Deferral Distribution Facility Deferral Customer Energy Management Renewable Energy Management Power Quality and Reliability
 <p>Figure 8. Microturbines manufactured by Capstone Turbine Corporation use natural gas or biofuels and drive high speed electrical generators</p>	<ul style="list-style-type: none"> Emerging market acceptance Relatively low cost (capital: \$700/kW, operating: \$0.015/kWh) Efficient at full load Lower SO_x than diesel generators 	<ul style="list-style-type: none"> High maintenance High temperature issues 	<ul style="list-style-type: none"> Rapid Reserve Customer Energy Management

Option	Advantages	Disadvantages	Applications
 <p>Figure 9. Real-time transactions to buy and sell power provides electric power producers and service providers a way of addressing competitive needs</p>	<ul style="list-style-type: none"> • No additional capital investment or physical resources required • Low cost (capital: <\$10/kW, operating: \$0.032/kWh) 	<ul style="list-style-type: none"> • Requires minutes to make transactions (too slow for instantaneous applications) • Uncontrolled and unreliable with current institutional structure` 	<ul style="list-style-type: none"> • Rapid Reserve
 <p>Figure 10. Peaking gas combustion turbine at Texas Utilities</p>	<ul style="list-style-type: none"> • Instantaneous response • Understood technology • High market acceptance 	<ul style="list-style-type: none"> • High maintenance • High temperature issues 	<ul style="list-style-type: none"> • Area Control and Frequency Responsive Reserve
 <p>Figure 11. FACTS depends on Westinghouse's solid-state STATCOM Switching Device to redirect power to under-utilized pathways</p>	<ul style="list-style-type: none"> • Makes existing infrastructure more useful • Uses well-understood solid-state technologies 	<ul style="list-style-type: none"> • Untried on a large scale • Unknown commercial costs 	<ul style="list-style-type: none"> • Commodity Storage • Transmission System Stability

Option	Advantages	Disadvantages	Applications
 <p>Figure 12. Recycling and energy recovery pilot plant (cogeneration) in California uses anaerobic composting to produce fuel gas that is dried and burned in an internal combustion engine to make electricity; extra gas fuels heaters, dryers, and steam boilers</p>	<ul style="list-style-type: none"> • Low initial capital cost 	<ul style="list-style-type: none"> • Siting and permitting barriers • Grid interconnection issues 	<ul style="list-style-type: none"> • Commodity Storage
 <p>Figure 13. Substation auto transformers like this one by Waukesha Electric Systems can manipulate taps to respond to 10 – 100 MVA transients</p>	<ul style="list-style-type: none"> • Well-understood, accepted technology • High market acceptance 	<ul style="list-style-type: none"> • Generally expensive • Large footprint • Long lead-time to purchase 	<ul style="list-style-type: none"> • Transmission System Stability
 <p>Figure 14. Distribution class capacitor banks made by Cooper Power Systems are typical of the parallel, series-parallel, or in a three-phase arrangement, 100, 150, and 200 kVar power ratings and 2,400 - to 21,600 - volt capacity</p>	<ul style="list-style-type: none"> • Inexpensive (\$25/kVar) • Well-understood technology • High degree of market acceptance 	<ul style="list-style-type: none"> • Large size to achieve needed capacities 	<ul style="list-style-type: none"> • Transmission Voltage Regulation

Option	Advantages	Disadvantages	Applications
 <p>Figure 15. Oil coolers for transformers like this Seimens model help keep temperatures down even during peak loading – as a result, transformers can support larger loads for longer times before overheating</p>	<ul style="list-style-type: none"> Well-understood technology High degree of market acceptance 	<ul style="list-style-type: none"> Environmental concerns 	<ul style="list-style-type: none"> Transmission Facility Deferral Distribution Facility Deferral
 <p>Figure 16. 100-foot, 12.5 kV, 1,250A underground transmission cable developed and demonstrated by Intermagnetics General Corporation, Southwire Company, and the US DOE was installed as a high-temperature (4K) superconducting cable</p>	<ul style="list-style-type: none"> Virtually loss-less transmission of electricity 	<ul style="list-style-type: none"> Expensive At advanced R&D stage of development (manufacturing limitations of cables with appropriate current density and cable length) Requires cryogenic operating environment 	<ul style="list-style-type: none"> Transmission Facility Deferral Distribution Facility Deferral
 <p>Figure 17. Fermilab's 1400-ton high-efficiency chiller</p>	<ul style="list-style-type: none"> Environmentally benign 	<ul style="list-style-type: none"> Inefficient Non-transportable 	<ul style="list-style-type: none"> Customer Energy Management




Option	Advantages	Disadvantages	Applications
 <p>Figure 18. Static Interruptible Power Supplies (UPSs) like Exide Electronics' One UPS Plus can deliver hundreds of volt-amperes to ride through momentary service fluctuations and outages</p>	<ul style="list-style-type: none"> • High market acceptance • Well-understood technology • Established infrastructure 	<ul style="list-style-type: none"> • Inefficient • Noisy • Slow to adjust to changing conditions • High maintenance 	<ul style="list-style-type: none"> • Power Quality and Reliability
 <p>Figure 19. Piller's Uniblock II rotary UPS combines digital control and power electronics with a rotating mass that provides inertia to drive a motor/generator for ride-through of momentary service fluctuations</p>	<ul style="list-style-type: none"> • High market acceptance • Well-understood technology 	<ul style="list-style-type: none"> • Short duration 	<ul style="list-style-type: none"> • Power Quality and Reliability
 <p>Figure 20. Seimen's SIPCON – DVR (dynamic voltage restorers) shown here in a turn-key, semi-trailer container; these units located between distribution and load provide power (MVA) and energy (hundreds of kilojoules) to improve power quality</p>	<ul style="list-style-type: none"> • Applicable to large-scale installations 	<ul style="list-style-type: none"> • Large size to achieve capacity 	<ul style="list-style-type: none"> • Power Quality and Reliability

Table 5. Functional Capabilities of Storage Technologies for Electric Power Applications

D – definite capability, L – likely capability, P – possible capability, U – unsuited to application

Applications	Electrochemical Storage Devices								Electromechanical Storage		Electrical Storage
	Flooded Pb-Acid	VRLA	Na/S	Ni/MH	Li/polymer	V-redox	Zn/Br	EC	Steel Rotor	Composite Rotor	SMES
Rapid Reserve	D	D	P	P	P	P	P	U	U	U	U
Area Control and Frequency Responsive	D	D	P	P	P	P	U	U	U	L	L
Commodity Storage	D	L	P	P	P	P	P	U	U	U	U
Transmission System Stability	D	D	P	P	P	P	P	U	U	U	D
Transmission Voltage Regulation	D	D	P	P	P	P	P	U	U	U	P*
Transmission Facility Deferral	D	L	P	P	P	P	P	U	U	U	P*
Distribution Facility Deferral	D	L	P	P	P	P	P	U	U	P	P*
Customer Energy Management	D	D	P	P	P	U	P	P	U	P	U
Renewable Energy Management	D	D	U	U	P	P	P	P	U	U	U
Power Quality & Reliability	D	D	P	P	P	P	P	L	D	L	D

* Some developers are considering SMES for transmission applications

Note: Table 5 does not address the disparate states of technological maturity and readiness to serve the application.

At present, flooded lead-acid, VRLA, SMES and flywheels are serving some of the applications in which they are identified as a likely or definite match. Flooded lead-acid batteries, though presently dominant in this set of electric power applications, are limited by size, weight, maintenance requirements and cycle life. If VRLA developers are able to make the technology more robust with respect to service temperature and recharge conditions, the technology has the potential to serve most of the battery storage applications. However, the weight of lead-acid technology will remain a limit to its portability, and even the reduced size of the VRLA technology with respect to flooded lead-acid batteries will not make it small enough in applications where significant energy demands and small footprint are both required.

The other electrochemical batteries, often considered “advanced batteries,” favorably complement the near-term VRLA option primarily for those

applications where higher energy is required and footprint/portability are important. The high operating temperatures necessary for sodium/sulfur batteries make them more efficient if they serve applications in which the battery cycles frequently and the thermal effects of cycling contribute to the maintenance of the operating temperature of the unit. These high temperature battery systems would serve applications with long periods of inactivity if the same battery system also served a frequent cycling application. The benefits of combining applications, discussed in Section 4.3 of this report, are significant and warrant detailed study and analysis. Because pumped electrolyte battery technologies require time to initiate dispatch of energy but can tolerate long periods of inactivity with virtually no loss of charge, zinc/bromine would serve infrequent-use applications in which instantaneous power is not required.

Lithium/polymer and nickel/metal hydride batteries, while proven in other applications, are just entering the electric power arena. Therefore, their likely

performance rating is a projection based on the known technical characteristics of the batteries and their performance under other applications that have similar requirements, including the power quality and reliability application under which lithium/polymer batteries have shown promise.

ECs are best suited for power quality and reliability applications. ECs provide many advantages over lead-acid batteries for mitigating or preventing power quality problems. Certain double-layer capacitors have at least five times the power density of batteries. Other advantages include:

- Charge/discharge cycle lives greater than 500,000 have been measured
- Conditions of charge/discharge do not affect life
- Lower cost than batteries per unit of power
- Use of carbon plastics and electrolyte materials that can be easily recycled.

Further improvements in the technology, especially those that reduce cost, will make this technology even more attractive in the future.

Steel rotor flywheels use the mass of the rotor (as opposed to high velocity) to achieve the momentum necessary to store enough energy for electric power applications. For this reason, steel rotor flywheels will be most useful when they serve applications that allow the rotor size to stay small (keeping both the weight and the safety concerns within bounds). They can then be used with other technologies (e.g., electrochemical batteries) to increase the energy capacity of the system. Composite rotor flywheels are in advanced stages of development and show promise to serve several of the applications shown in Table 5 and store significantly more energy than steel rotor flywheels. However, certification of the composite flywheels' compliance with the American Society for Testing and Materials (ASTM) standards will be necessary. Since composite flywheels depend primarily on high speed (as opposed to mass) to achieve the necessary power and energy levels, they also depend on high-strength fibers to permit lightweight, high-speed rotation. Unless the cost of the fiber material (advanced carbon fibers) falls significantly, composite rotor flywheel systems will be limited to applications with low duration discharge (energy).

The technical and economic challenges to building a high-energy SMES have encouraged developers to focus on micro-SMES devices that serve short-duration discharges. The ability of SMES to address

transmission applications exploits the fact that many transmission issues begin with a transient event that rapidly grows to unmanageable proportions. The high power capacity and quick response capability of SMES allows it to dispatch in a way that could prevent transmission transients from growing, and energy considerations would be less important.

The commercially available storage media for energy storage systems are, in general, not economically attractive for large, high duration generation applications (e.g., Commodity Storage) because traditional spinning mechanical technologies are more cost effective. However, advanced battery developers hope to take advantage of economies of production to make their technologies more cost competitive. Composite rotor flywheel manufacturers plan to modify their designs to comply with ASTM standards and to develop bearing systems with lower friction losses and longer life. Both of these improvements would significantly enhance the ability of composite rotor flywheel systems to serve high-energy applications.

4. Necessary Future Work

4.1 Cost Breakdowns for Comparison of Storage Systems to Alternatives

During the Phase I Opportunities Analysis, participants realized that direct comparisons of costs of an energy storage system with a more conventional technology was virtually impossible because the cost sources are so disparate. In response, Phase I analysts developed a cost breakdown that made comparison of technologies more approachable, though still quite difficult. That approach considered the following cost components:

- Interfaces to the AC load and source
- Power conversion system to convert between utility AC power and storage-media-compatible form
- Storage medium
- Monitors and controls for all subsystems
- Building or shelter, transportation of the system including shipping costs and permits
- Engineering services and training to start-up and operate
- Operation and maintenance costs.

The Phase I approach to standardizing cost breakdown also considered the cost of financing the

purchase, installation and operation of the system. While the approach did make a more direct comparison easier, it did not completely resolve the problem. Phase II work identified the need to add the costs of additional peripheral subsystems such as vacuums, bearings, cryogenics and safety systems to make direct comparison with traditional technologies and comparison between various energy storage systems. Also missing from the Phase I cost breakdown was the cost of disposing of spent storage media during the system's service life and decommissioning the storage system after its service life is complete.

Decommissioning cost considerations are especially relevant for components of the systems that may be considered hazardous materials and must be disposed of at a Federally-permitted facility (sodium, sulfur, bromine, lead, sulfuric acid, sodium polysulfide, chromium used to coat sodium/sulfur containers for corrosion protection, etc). Many system manufacturers are offering reclamation and recycling of the spent storage media and purchasers will not directly bear those costs. However, decommissioning is a part of the system cost and should be considered for direct comparison. For any system, demolition permits, labor and material disposal (including landfill permits, portage and tipping fees) will be important decommissioning costs.

Because market acceptance of energy storage systems correlates closely to costs and economic competitiveness, development of a cost breakdown structure that facilitates direct comparison would be an important improvement to the advancement of energy storage in the nation's electricity infrastructure. As shown by the number of items missing from the first attempt to develop a standardized, comparable costing system, the complexity of developing such a system warrants its treatment as a separate study unto itself. The modifications suggested in the Phase II analysis that would support such a future effort appear in Appendix D.

4.2 Markets and Benefits of Energy Storage in the Competitive U.S. Electricity Industry

Possibly the most elusive, yet critical pieces of information regarding energy storage in electric power applications are the future markets and national benefits of its adoption. The report of the Phase I analysis published the first attempt at projections of the markets and benefits. Phase II sought to update and refine those projections. All of the obstacles to the first projection and several new obstacles hampered such revision.

Market estimates for the energy technologies under consideration depend on valid estimates of the scope of the applications that they serve and realistic assessments of the market share that the technologies

might claim. In the changing electric power industry, the prevalence and value of applications are very uncertain. None of the industry participants in Phase II believed that any fixed size or value for any application would have a defensible basis given the shifting nature of the industry. Similarly, the changing nature of the industry makes information-sharing a strategic risk for study participants who are (or may tomorrow be) direct competitors for the same market. As a result, the ESS Program elected to pursue assessment of markets and benefits as a separate effort outside of the working group structure of the Phase II Opportunities Analysis.

The development of market estimates is essential to decision-making among manufacturers considering investment in manufacturing facilities and marketing strategies for energy storage technologies. The results of the market estimate influence the projections of system cost which, in turn, affect potential end-users' likelihood of considering energy storage as a viable option. Both the manufacturers' and the end-users' decisions affect the potential national benefits from the adoption of energy storage and the decisions of Federal energy programs regarding R&D investment in energy storage. Therefore, work toward developing market and benefits estimates is an important facet of the necessary future opportunities analysis for energy storage. Appendix E presents a list of resources that could be useful in that effort.

4.3 Multiple Applications to Increase Benefits of a Single Energy Storage System

In the Phase I study, participants identified groups of multiple applications in which combinations of individual applications increased the benefits offered by a single energy storage system. As that study included only electrochemical batteries and did not consider electromechanical or electrical storage devices, the groups of applications identified were not complete. However, the approach to identify those groups remains a valuable tool to the identification of multiple applications for the technologies now under consideration. The process of comparing applications requirements and pairing them to storage technologies, like the process of estimating markets and benefits for these diverse technologies, was too extensive to address under the umbrella of the Phase II work. Therefore, this work should be part of a future project to assess markets and benefits in a competitive electric utility industry.

Appendix A. Technical Approach for the Phase II Analysis

The success of the Phase I Opportunities Analysis suggested that the direct involvement of expert stakeholders in a series of working meetings was a highly effective approach to identify and analyze opportunities for energy storage. Therefore, like the Phase I process, the Phase II process gathered representatives from numerous stakeholder groups to meet and provide input to this project.

Also like the Phase I project, Phase II consisted of two, two-day working meetings of the expert stakeholders. The first meeting was held in November 1998 and the second in April 1999. In the first meeting, the group assessed the present state of knowledge of utility energy storage applications, reviewed the Phase I definitions of applications and their requirements and revised those definitions. In the second meeting, participants refined the application definitions and made presentations on their respective technologies and the applications that could be addressed by them. The group members reviewed each presenter's claims for his/her technology's capabilities and reached consensus regarding them. Table 5 of this report presents the consensus views. Uncertainty regarding the effect of emerging competition and sensitivity regarding market data will make future assessments of energy storage markets, benefits, and cost breakdowns more difficult.

Organizations interested in energy storage technologies today are confronted by a dizzying array of choices. Although flooded, lead-acid batteries dominate the rechargeable battery market, other battery technologies are maturing and closing the gap. David Linden's *Handbook of Batteries* for example, lists 24 different battery chemistries. In addition, flywheels, SMES, and electrochemical capacitors increase the number of technologies to consider and increase the need for a concise study of energy storage technologies to choose a workable crosscut of potential candidates for deployment in utility applications.

Some battery chemistries are relatively easy to dismiss as potential candidates. For example, non-rechargeable batteries were not included on the list of potential candidates as utility applications require rechargeable batteries. Rechargeable batteries required more careful consideration. For this reason, analysts established criteria to chose technologies

that were both advanced enough in their development to be viable candidates for the storage applications under consideration, but still required additional systems or component development for full market acceptance.

A key example of a technology that supports this rationale is lead-acid batteries. Lead-acid batteries including their variants, flooded and valve-regulated, are both advanced in their development and mature in their penetration of some markets. However, they have some technical deficiencies and are not immature technology for large-scale stationary applications. Lead-acid batteries are a benchmark against which all other storage technologies are compared, thus making their inclusion in the report mandatory.

Fuel cells were not included in this study even though they are a potentially viable candidate for some energy storage applications. Fuel cells, however, are fundamentally different in that a fuel cell both generates and stores energy. Further, fuel cells process energy external to the storage device. A fuel cell storage system is not directly, electrically recharged. Fuel cells may be included in a future assessment of utility storage applications as the technology matures.

Based upon the two criteria identified above, the following storage technologies included in this study:

- lead-acid batteries, (flooded and valve-regulated)
- lithium/polymer batteries
- nickel/metal hydride batteries,
- sodium/sulfur batteries
- vanadium-redox batteries
- zinc/bromine batteries
- flywheels (steel and composite rotors),
- superconducting magnetic energy storage and electrochemical capacitors.

Appendix B. Organizations Participating in the Phase II Opportunities Analysis

As noted in the acknowledgements to this report, many organizations devoted their resources to advancing the understanding of applications requirements in the emerging electric power industry and the markets and benefits for energy storage in those applications. The following list describes the organizations that directly contributed to this effort.

Energy Service Providers

investor-owned utilities, energy-service companies, electric cooperatives, utility trade organizations

Enron Energy Services

Enron Energy Services, a subsidiary of Enron Corp., partners with commercial and industrial businesses to provide integrated energy and facility management outsourcing solutions on a national basis. Enron's innovative approach to energy delivery and management frees customers to focus critical resources on their core business while Enron assumes the responsibility of managing energy and facility costs. Enron is one of the world's leading integrated natural gas and electricity companies. The company owns approximately \$30 billion in assets and produces electricity and natural gas, develops, constructs and operates energy and water facilities worldwide and delivers physical commodities and risk management and financial services to customers around the world.

Northern States Power (now part of Xcel Energy)

Northern States Power (NSP) Company, founded in 1916 and headquartered in Minneapolis, Minnesota, is a major investor-owned utility with growing domestic and international non-regulated operations. NSP and its subsidiary operate generation, transmission and distribution facilities to provide electricity to about 1.4 million consumers in Minnesota, Michigan, Wisconsin, and North and South Dakota. NSP and its subsidiary also provide a wide variety of energy-related services throughout these service areas. NSP operates two nuclear plants, five major coal plants, hydroelectric plants, wind turbines, and several facilities that burn refuse-derived fuel, oil, wood and gas. Renewable sources like wind and hydro account for about 3% of NSP generation. Refuse-derived fuel and waste wood produce about 1% of the company's electricity.

Public Service of New Mexico

Public Service of New Mexico (PNM) is a combined gas and electric utility that serves about 1.2 million people in 100 communities throughout the state of New Mexico. In addition to retail gas and electric, PNM sells power on the wholesale market, operates a water utility in Santa Fe and offers many energy-related services. While 51% of the people served by the company reside in or near Albuquerque, PNM provides gas and electric service to a large geographical portion of NM. PNM has formed four strategic business units: Electric Services provides retail electricity to customers; Gas services delivers both gas products and services to customers; Bulk Power Services manages the generation and transmission system in the state to deliver wholesale and retail electricity in the state and throughout the region; Energy Services provides a variety of new energy-related services that are based on PNM's management and technical expertise.

Southern California Edison

Southern California Edison (SCE) is the second largest electric utility in the United States, serving over 11 million customers in a territory of 50,000 square miles. The largest subsidiary of Edison International, Inc., SCE was established in 1887. In a project with the Electric Power Research Institute and other organizations, SCE worked to design, install and operate a 10-MW, 40-MWh battery energy storage system for a demonstration of utility scale load leveling in Chino, CA in the late 1980s. The design was based on the BEWAG system in Germany, and was the template for the PREPA system in Puerto Rico. Recent reorganization at SCE prompted by emerging competition resulted in the formation of five distinct business units: Customer Solutions, Distribution, Generation, Power Grid (responsible for bulk power transmission) and QF (responsible for power purchase contracts with third-party generators). The Chino storage demonstration was complete at the time of the reorganization and the facility has been decommissioned.

Southern Company

The Southern Company is the umbrella organization for 17 electric utilities throughout the United States, South America, Caribbean, China, Philippines, and the European Union Countries. It is one of the largest producers of electricity in the world, generating over 50,000 MW of electricity in 1999. Southern Company products and services include electricity generation, natural gas storage and management, and wholesale energy trading and marketing. Net income for 1999 was \$1.3 billion on revenues of about \$11 billion. Southern Company assets in 1999 were worth approximately \$38 billion.

Manufacturers

batteries/BES systems, flywheels/FES systems, supercapacitors/SCs systems, superconductors/SMES systems, power electronics, renewable hybrid systems, trade organizations

Active Power

Active Power manufactures a steel flywheel called the CleanSource Flywheel. This 7000-rpm flywheel, when connected to a power conversion system, provides 400 kW of DC power for 5 seconds, but varied combinations of power and discharge duration are possible with the same rotor. Also, two or more rotors can be combined to serve loads up to 800 kW or more. Active Power has chosen not to integrate a power conversion system into its flywheel, instead making its technology more readily incorporated into a current UPS product. Active Power plans to market its products in power quality and battery extension applications. Active Power has pursued a steel flywheel as opposed to a composite fiber flywheel for several reasons: low-cost, safety and high power density. At \$150/kW installed, the CleanSource flywheel is significantly less expensive for short duration applications than composite flywheels and has promise to serve those applications. Active Power does not envision their product serving longer-duration applications unless it serves in a hybrid system with another technology that is more economic at longer durations of dispatch.

American Superconductor

ASC is a manufacturer of SMES and installed their first SMES unit in 1993. The company now has 9 installations worldwide, and is currently developing and marketing SMES devices for utility power quality applications. Their standard turn-key product, configured in a semi-trailer, can deliver 1 MW for 1 second quickly enough to prevent sensitive equipment from suffering interruption of electrical service. The SMES magnet is made of a low temperature superconducting material that requires liquid helium-based cryogenics. ASC has introduced a new SMES product with a more sophisticated cryogenic design than their earlier products. The improvements to the system reduced the electrical load to cool the unit significantly. The new design SMES system can sustain normal operation for about 200 hours after an unplanned shutdown of the refrigeration system. This "micro" SMES unit is suited to power quality applications.

Electricity Storage Association

The Electricity Storage Association (ESA) is an industry trade organization founded by eight electric utilities in 1990 that perceived a viable role for energy storage in electric power applications. Originally focused on battery energy storage, the organization was founded as an informal association as the Utility Battery Group, and later incorporated as the Energy Storage Association. The ESA is now a membership trade association that has the mission of fostering development and commercialization of competitive and reliable energy storage delivery systems for use by electricity suppliers and their customers.

GNB Industrial Technologies

GNB Industrial Technologies is one of the world's largest manufacturers and recyclers of lead-acid batteries. GNB has plants in North America, Australia, and New Zealand, and manufactures, distributes and recycles lead-acid batteries for industrial, automotive, heavy-duty and specialty applications around the world. GNB has been building batteries for over 100 years and is closely connected with Ford Motor Company, supplying batteries to its automotive, truck and tractor division. GNB also supplies batteries to the United States Navy for its submarines and to the United States Air Force for Peacekeeper missile silos. GNB has formed a teaming relationship with General Electric on several battery energy storage system projects, and has attended meetings of the Energy Storage Association since its inception.

Intermagnetics General Corporation

IGC gained significant experience with superconducting magnets from development of Magnetic Resonance Imaging (MRI) equipment. IGC's SMES systems include liquid helium cryogenics and power electronics that allow the system to respond to voltage sags, spikes and electrical interruptions. An IGC unit recently installed at an Air Force base includes a 6MJ superconducting coil, a closed-loop cryocooler, and off-the-shelf power conversion and remote monitoring units. Housed in a mobile/relocatable shelter, the system is designed to minimize on-site engineering. The system is intended for unmanned operation, similar to commercially available UPS systems. IGC remains highly active in MRI devices and in R&D of high-temperature superconducting materials (still cryogenic) that could eventually replace the low temperature devices that are currently fielded.

Maxwell Energy Products

Maxwell focuses on two core competencies: pulsed power and industrial computers. Within its pulsed power thrust, the company includes research, development and sales of numerous energy products. These devices include ceramic capacitors for military and industrial use, electromagnetic interference filters for implantable medical devices, high-voltage energy storage and discharge capacitors for medical, industrial, research and defense applications, and ultracapacitors that provide electrical energy at high power for up to 45 seconds. These ultracapacitors are useful for consumer electronics, power quality devices and automotive applications. Coupled with the products in the company's Phoenix division: power conditioning, power distribution and power supply systems, ultracapacitors have the potential to serve in a number of energy storage applications of interest in this study. Maxwell manufactures ultracapacitors through its subsidiary Power Cache, and has 6 sizes commercially available.

Omnion Power Engineering Corporation

Omnion Power Engineering Corp. (now the Power Electronics Division of S & C Electric Co.) has been developing advanced power systems, power system components and system controls since 1971. Omnion has become recognized as the leading supplier in this country of power electronics and system controls for utility interconnected advanced energy systems. Omnion was the developer of the PQ2000, a 2000 kW for 10 seconds transportable power quality system which won an R&D 100 award in 1997. This system was the predecessor of the Mobile PQ2000, a trailer-mounted, power quality system that can deliver up to 2 MW for 15 seconds to overcome brief power disturbances.

ZBB Energy Corporation

ZBB Energy Corporation (ZBB) is a Wisconsin-based developer of proprietary zinc/bromine battery technology. The company also maintains research and development laboratories and regional marketing and administrative offices in Perth, Western Australia. ZBB's main product is large-scale (capacity) advanced technology batteries for the storage of power from a variety of generating sources. The zinc/bromine technology is typically designed as an aqueous flow battery, using a circulation loop to continuously feed reactants to the battery stacks. The battery can be fully discharged repeatedly without any damage to the system and has a life of at least 1,500 full charge/discharge cycles. This battery is ideally suited to applications that require deep-cycle and long-cycle life. Typically these battery systems range in capacity from 50 kWh in a single, three-stack module, up to 500 kWh in multiple modules arranged in series and parallel arrays.

Industry Consultants

research organizations, consultants

Energetics, Incorporated

Since 1979, Energetics (a subsidiary of VSE Corporation) has provided energy and environmental consulting services for private industry and Federal clients involved in technology research, development, demonstration, assessment and commercialization. Expertise includes advanced technology assessment, technical and economic feasibility analysis, technology transfer, R&D planning, modeling and simulation engineering studies, market assessment, strategic resource management, regulatory analysis, environmental compliance and risk management—especially as related to energy supply and end-use industries and technologies. Specific technology areas include industrial and building technologies, transportation technologies, advanced fuel and generation technologies, transmission and distribution technologies and distributed resource technologies. Energetics' work in energy storage and hydrogen crosscut these areas and address technologies that include battery energy storage, SMES, flywheel energy storage, fuel cells, hydrogen storage, power conversion systems and pumped hydro.

International Lead Zinc Research Organization

The International Lead Zinc Research Organization (ILZRO) was formed in 1958 as a non-profit research foundation for the purpose of conducting research on behalf of the international community of lead and zinc miners and smelters. Since that time, ILZRO's membership has grown to include significant numbers of end users of these metals from among the steel, automotive, die casting, battery, galvanizing and other industries. ILZRO contributes to the development of environmentally-appropriate markets for lead and zinc by discovering and developing new uses and improving existing uses and by furnishing technical information to organizations that will adopt and/or promote those uses. ILZRO's R&D portfolio for 1999-2000 covers most major areas of lead and zinc consumption, such as batteries, coatings and die castings, as well as significant work in the areas of the environment and human health.

Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory for the U.S. Department of Energy (DOE) and is managed by Sandia Corporation, a subsidiary of Lockheed-Martin Corporation. Sandia's mission involves engineering and development of technologies for national security and it works with government, industry, academia and other research and development organizations on a wide range of advanced technologies. The DOE Energy Storage Systems (ESS) Program is conducted by Sandia and involves systems integration, component development, prototype testing and systems analysis. Many ESS projects are performed in collaboration with private sector organizations as well as by technology specialists at Sandia. The Opportunities Analysis was an ESS analysis project managed by Sandia and contracted to Energetics, Inc. Sandia's role was to provide overall project guidance and direction, to review the technical results and conclusions of the study and provide technology information when appropriate. Several Sandia staff members attended and participated in the Opportunities Analysis meetings and contributed to the technical content of the project.

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Appendix C. Fact Sheets for Ten Electric Power Applications of Energy Storage

Rapid Reserve

Area Control and Frequency Responsive Reserve

Commodity Storage

Transmission System Stability

Transmission Voltage Regulation

Transmission Facility Deferral

Distribution Facility Deferral

Renewable Energy Management

Customer Energy Management

Power Quality and Reliability

Rapid Reserve

NERC requires utilities to avoid interruption of service to customers, even if an electrical generating unit fails. The reserve power supply must have instantaneous response to comply with NERC Policy 10 requirements. Satisfying this requirement can represent a significant cost to power producers.

Because cold thermal power plants require hours, and combustion turbines require a half-hour to get generators ready to accept load, utilities operate thermal plants and combustion turbines at less-than-full capacity to keep generators hot and spinning and ready to provide reserve power. Energy storage can help utilities maintain rapid reserve, reduce or eliminate the need for supplemental power from combustion turbines, and free thermal plants to generate at full capacity (for greater efficiency and economy). Storage systems designed for rapid reserve can replace generation units that fail, and provide power until the utility brings other sources of power on-line or repairs the failed unit.

Since the power plants that they would temporarily replace have power ratings in the order of 10 to 100 MW, storage systems for rapid reserve must have power capacities in this same range. Generation outages that require rapid reserve typically occur about 20 to 50 times per year. These outages occur randomly. Therefore, storage facilities for rapid reserve must be able to address up to 50 significant discharges that occur randomly through the year.

Figure C-1 illustrates the generation capacity of a utility for a typical week in which a significant failure occurs; the balloon shows the detail of the capacity loss and recovery with appropriate resources. Figure C-2 shows how storage would respond to the demand to maintain the utility's ability to satisfy the load.

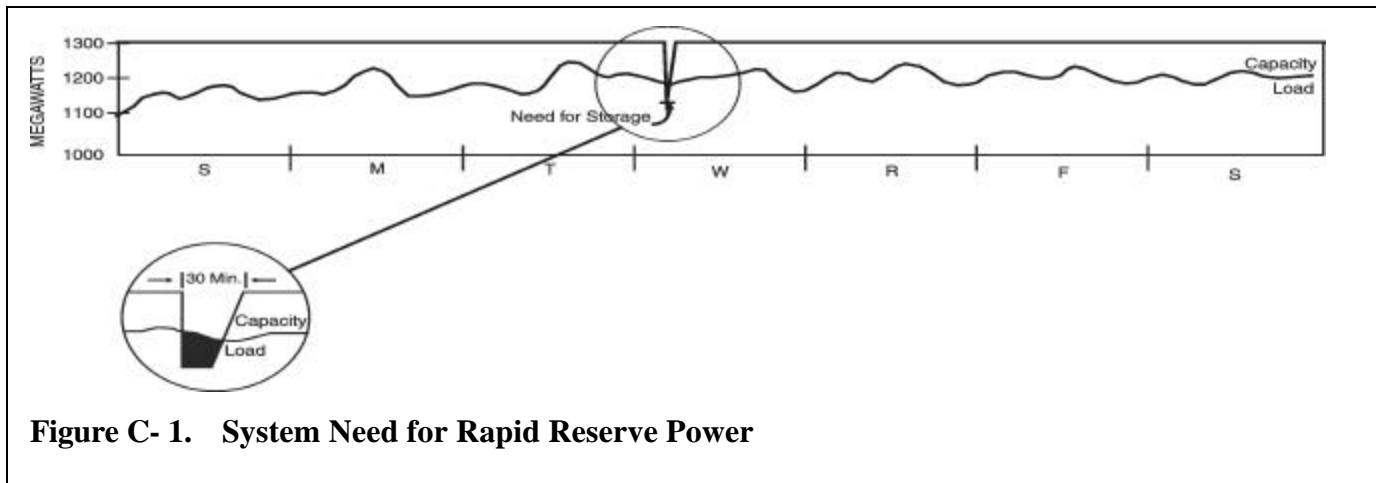


Figure C- 1. System Need for Rapid Reserve Power

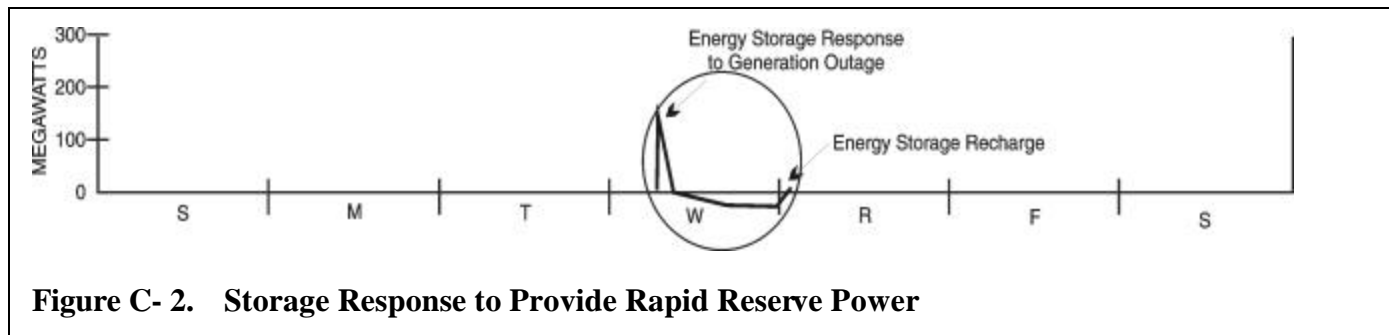


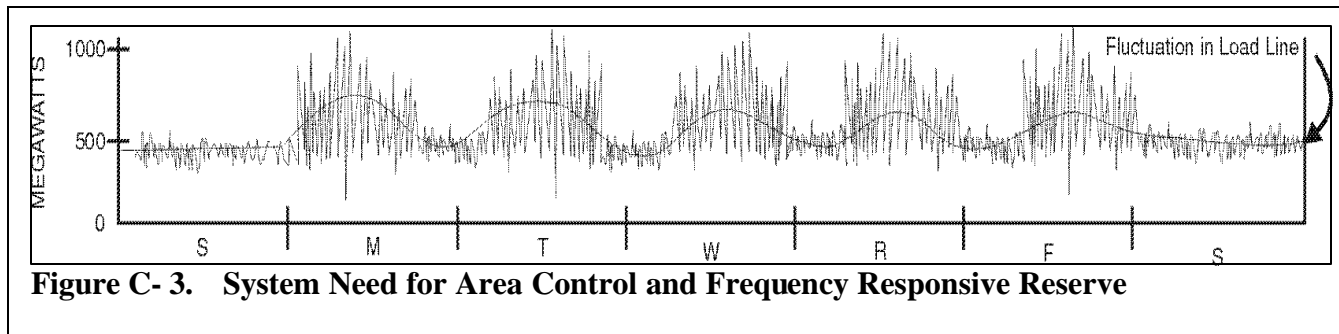
Figure C- 2. Storage Response to Provide Rapid Reserve Power

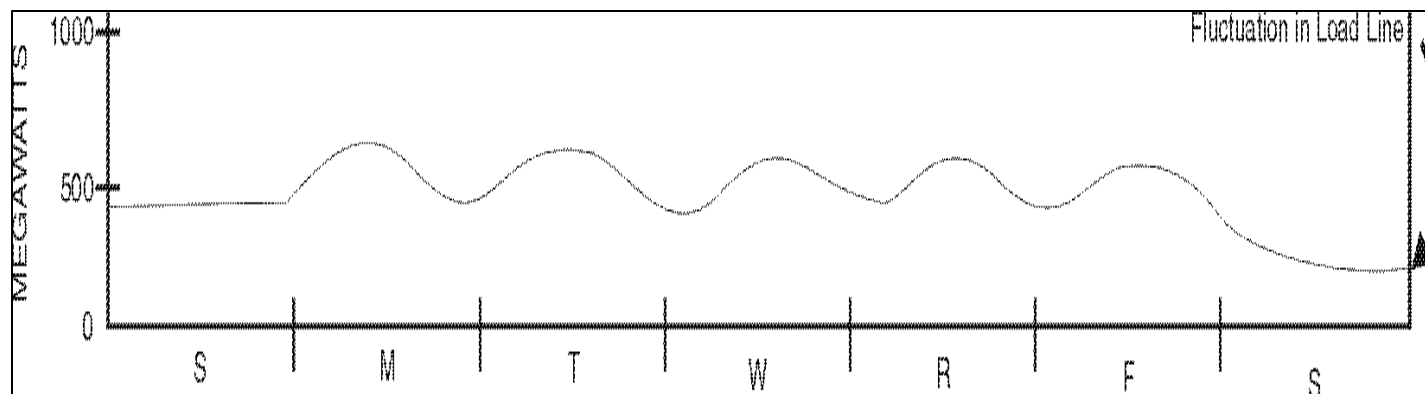
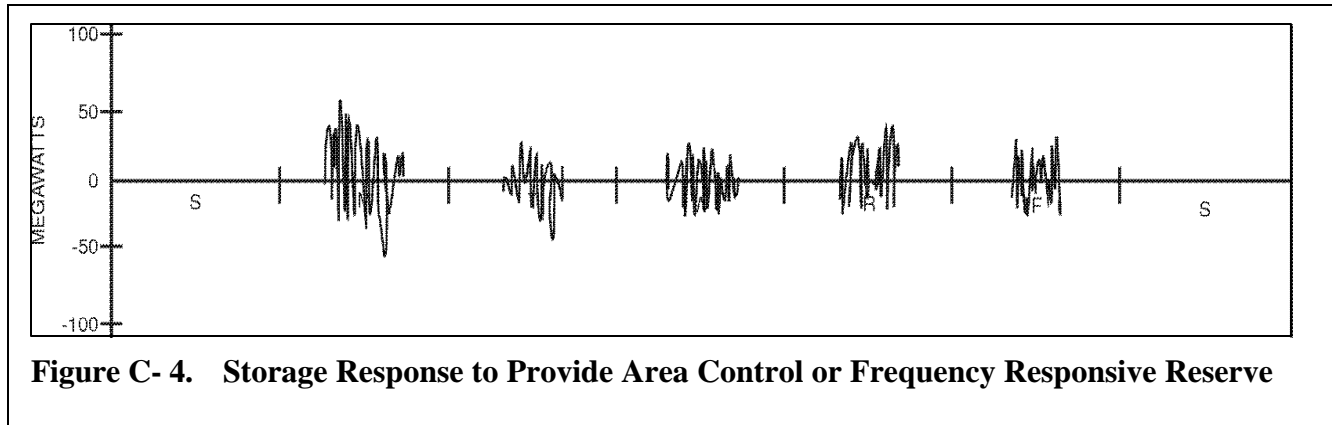
Area Control and Frequency Responsive Reserve

NERC requires that electric power producers deliver power to and draw power from their neighbors according to prearranged power transfers. This requirement stems from the fact that large changes in electrical load affect the operating speed of generators at power plants. The frequency of the electricity that the generators produce depends on the operating speeds of the generators. When the electrical frequency differs significantly from the 60 cycles per second (Hz) for which electrical equipment in the United States is designed, both the customers' equipment and the utilities' generators can be damaged. To regulate frequency, utilities can install storage systems that discharge to meet rising load, and charge when loads fall-off. In this way, the storage system protects the generator from the fluctuation in load, and prevents subsequent frequency variations.

Isolated utilities are not subject to neighbors' power fluctuations, but these utilities—with no connection to a large stabilizing grid—are very vulnerable to customers' load-switching and failures of small generation plants. Isolated utilities have no neighbors from which they can draw or to which they can feed power. They must balance the generation and load without outside resources. To achieve such area regulation and frequency control, both interconnected and island utilities can install storage systems to accept unwanted power during customer load-drop and deliver additional power during customer load-rise or during an outage of a small generating station. Such storage systems would have to deliver on the order of 10 to 100 MW to absorb and deliver power as it fluctuates. The system would have to be able to dispatch continuously, especially during peak load times in frequent, shallow charging and discharging that would occur. Peak loading may occur up to 250 weekdays each year for most utilities, and the fluctuations are numerous during those periods, but have total durations of ten minutes or less. During low demand periods, when conventional equipment provides frequency and area control, and the storage system would be inactive.

Figure C-3 shows unscheduled power imbalances between one utility's power output and the power level of neighboring utilities on the grid. Figure C-4 shows how storage would respond to help maintain a scheduled transfer of power and Figure C-5 illustrates the effect of storage on the utility service.



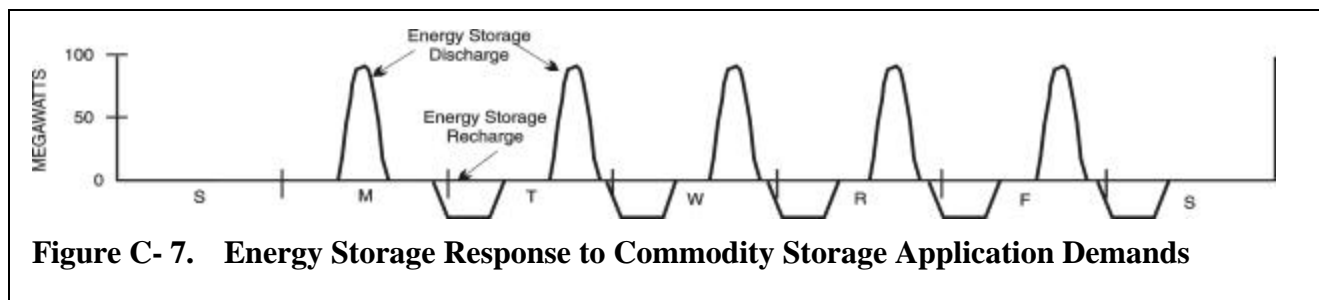
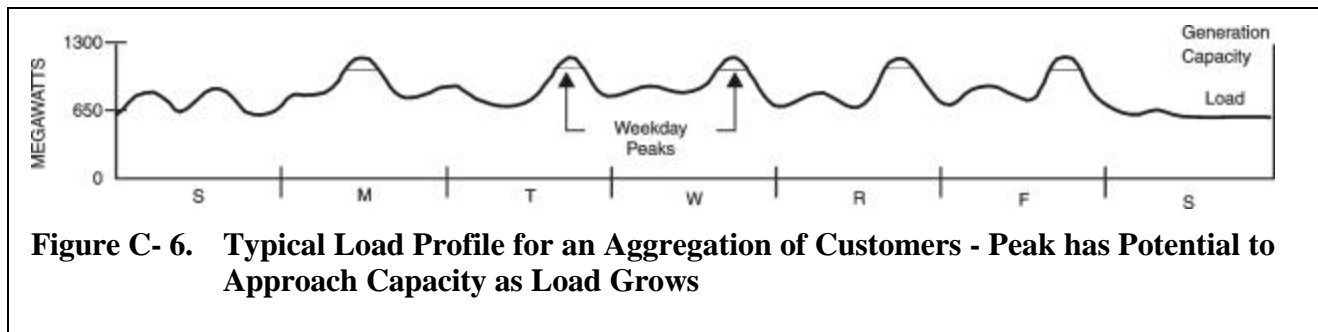


Commodity Storage

During peak load times, utilities often need to operate costly combustion-turbine units to meet customer demands. With energy storage, utilities can store electricity produced by inexpensive base-loaded units during off-peak hours and discharge power during peak demand times. Leveling out the load demand in this way allows utilities to improve profitability by selling power produced during off-peak times at premium on-peak rates. Although commodity storage (previously referred to as “load leveling”) was the first application that utilities recognized for energy storage, the differences in the marginal cost of generation during peak and off-peak periods for many utilities are quite small. Therefore, commodity storage is generally a secondary benefit that utilities derive from an energy storage system installed for other applications that offer greater economic benefits.

Commodity storage applications require energy storage systems that are on the order of at least 1 MW and up to hundreds of MW. The systems must have several hours of storage capacity (between two and eight hours). For utilities without a seasonal demand variation, a system used for commodity storage would operate on weekdays (250 days per year). For utilities that experience seasonal peaking, commodity energy storage systems might operate much less frequently. Operation would be clustered during seasonal peaking months.

Figure C-6 shows a typical utility load shape and the amount of peaking reduction that an energy storage system used for this application would have to supply. Figure C-7 shows how storage could offer electricity on-demand, using low-cost power as a high-priced commodity.



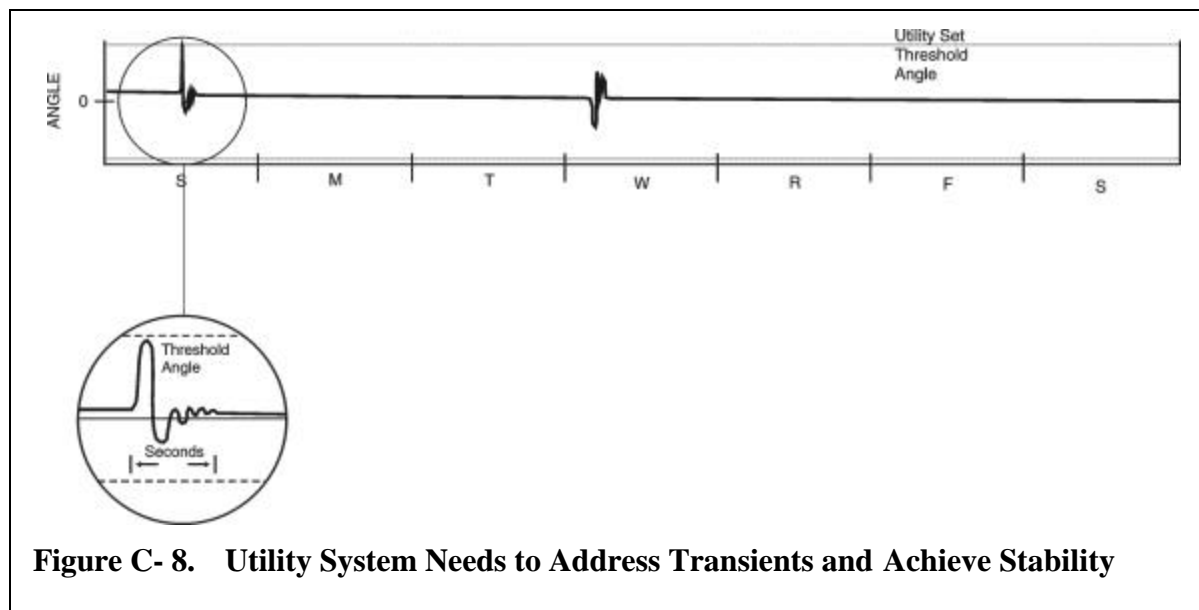
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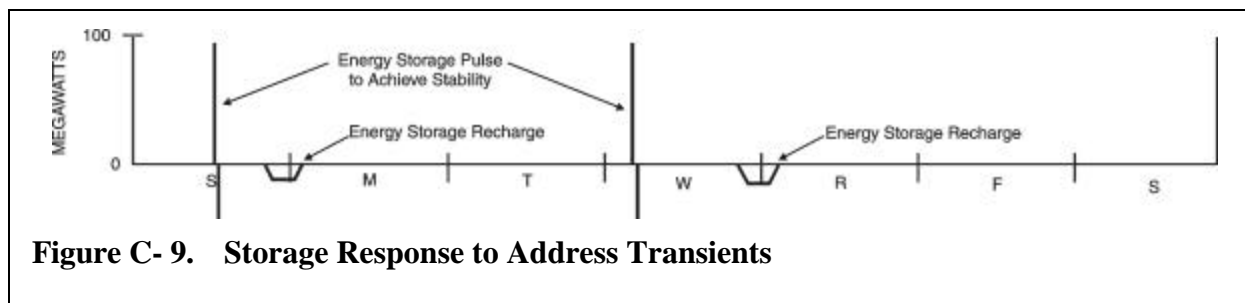
Transmission System Stability

NERC requires numerous safeguards regarding the stability of the nation's transmission system. These safeguards are the topic of debate as the country moves to a competitive electricity industry and power providers seek ways by which they can avoid the cost of maintaining stability. This problem is especially difficult since many events in routine utility operation can cause instability in transmission systems. Events as common as customers switching loads, lightning strikes, and generators going on or off-line cause generators in the system to fall out-of-sync with the rest of the system. The difference between the phase-angle of a generator and the phase-angle of the load-end of the transmission line measures the synchronization and stability of the system. If the difference between those angles is too large and the utility cannot quickly (within a few cycles) damp unstable oscillations, the power system can collapse. In this very undesirable circumstance, the utility must shut down and restart its equipment to resynchronize the system.

Energy storage systems can help utilities maintain synchronous operation of their systems by discharging to provide power and charging to absorb power as system loading conditions change. Energy storage systems for transmission line stability require power in the 100s of MW, have a self-commutated converter (to provide real and reactive power), and have enough storage capacity to discharge at full power from a minute up to hours. Energy storage system operation could typically occur about 100 times annually.

Figure C-8 illustrates two instances of transmission line stability; both events take the generator away from synchronous operation with the system, and toward an angle difference that could cause system collapse. The balloon shows an expanded time-scale of the first transient event, and the generator's return to stable operation. Figure C-9 shows the energy storage system discharging and charging multi-megawatt pulses into the system to counter instabilities.



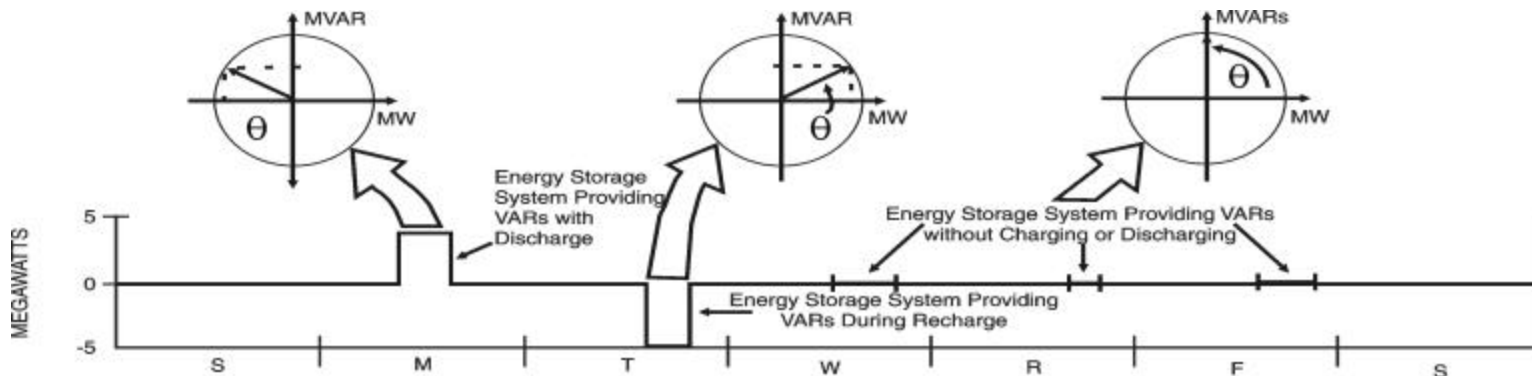
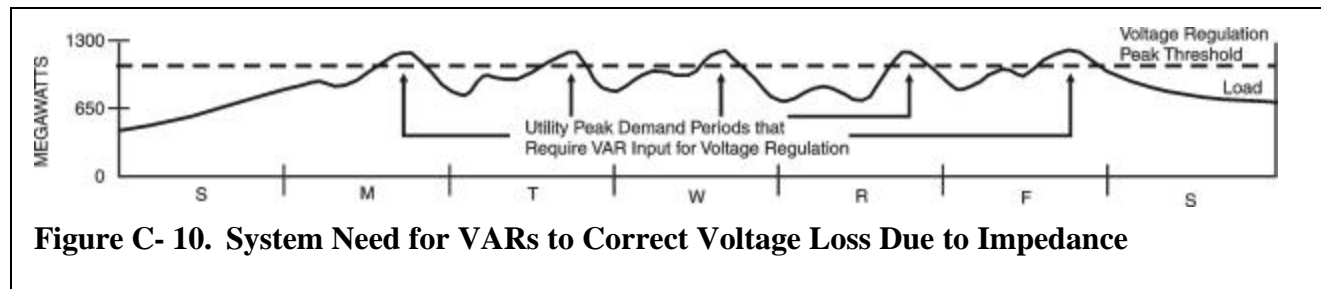


Transmission Voltage Regulation

Without corrective measures, impedance in transmission lines causes the voltage at the generation-end of a line to be greater than voltage at a load location at the other end of the line. To offset this effect, utilities inject reactive power and maintain the same voltage at all locations on the line. Traditionally, fixed and switched capacitors have provided the reactive power (VARs) necessary for voltage regulation. An energy storage system that a utility has installed for some other primary application can provide VARs to the system to augment existing capacitors and replace capacitors planned for future installation.

An energy storage system can provide VARs during discharge, charge, or inactivity. For this reason, utilities can use energy storage systems in megawatt sizes (that have other primary functions in the utility) to achieve voltage regulation on the order of 1 to 10 MVARs. The energy storage system for voltage regulation must provide MVARs for 15-minutes to an hour during daily load peaks (250 times per year). Peaks might not happen as frequently in regions where loading is seasonal. The power conversion system must be self-commutated to provide reactive power.

Figure C-10 illustrates high-demand times that might require voltage regulation. Figure C-11 shows an energy storage system operating to provide VARs during discharge, charge, and inactivity. The circular plots associated with voltage regulation periods show real and reactive power the system provides. As inferred by the plots, the relative magnitudes of VARs and watts that the system provides are not independent, and the inverter must be large enough to provide VARs while discharging at full real power levels.



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Transmission Facility Deferral

When growing demand for electricity approaches the capacity of the transmission system, utilities add new lines and transformers. Because load grows gradually, new facilities are designed to be larger than necessary at the time of their installation, and utilities under-utilize them during their first several years of operation. To defer a line or transformer purchase, a utility can employ an energy storage system until load demand will better utilize a new transformer.

Utilities sometimes define the demand at which they need to add transmission facilities as the load at which the transmission system can continue full operation in the event of the loss of one line or transformer. In Figures C-12 and C-13, the utility has applied this evaluation technique to two 100-MW transmission lines. One power line can carry the entire load during a period of low demand. However, during a high demand time, a single line cannot provide the power that is needed. Although the transmission capacity does not satisfy the evaluation criterion, existing demand would not fully utilize a third line. The utility could meet the load demand with an energy storage system and defer an expensive facility upgrade.

Figure C-14 shows an energy storage system operation to help a single transmission line to meet peak demand. Operation would occur 100s of times per year, mostly during seasonal peaks (when heavy load demand on the lines is more likely). The power requirement for this application would be on the order of 100s of kW or several hundred MW. The energy storage system would need to provide one to three hours of storage to provide support to the constrained transmission facility.

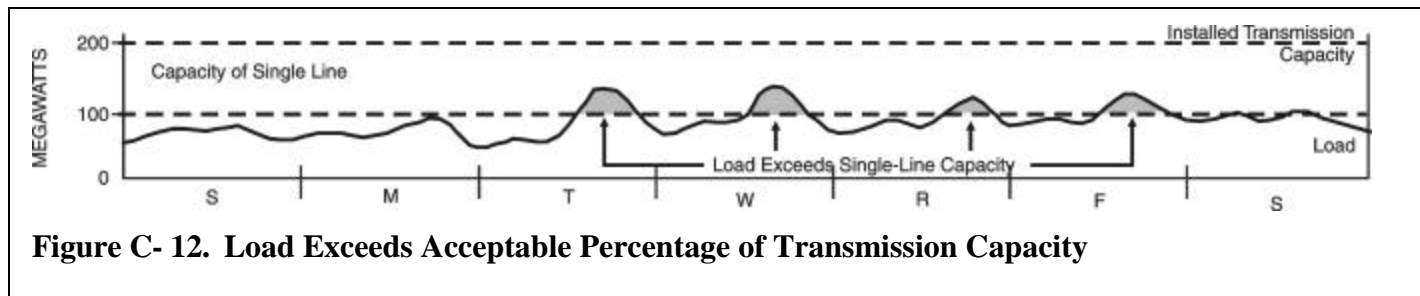


Figure C- 12. Load Exceeds Acceptable Percentage of Transmission Capacity

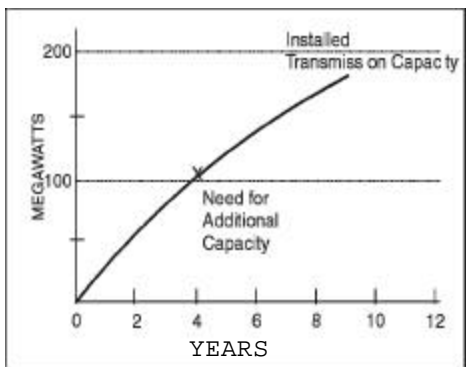


Figure C- 13. Transmission Load Grows to Meet Demand

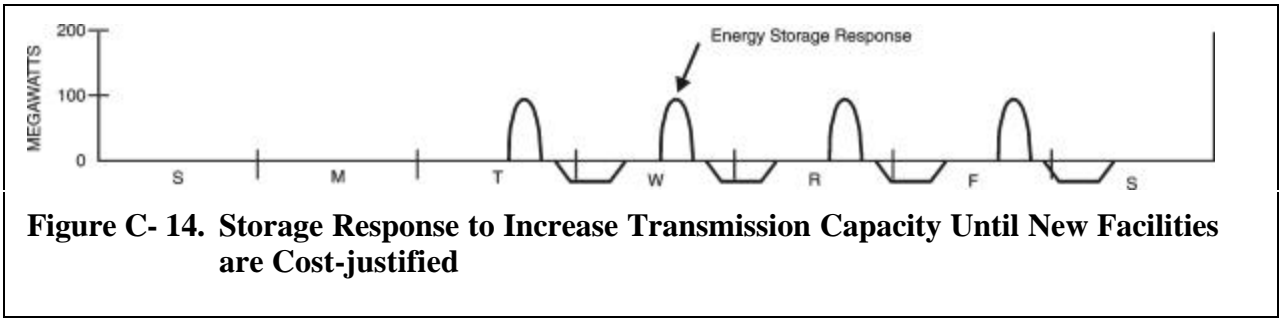
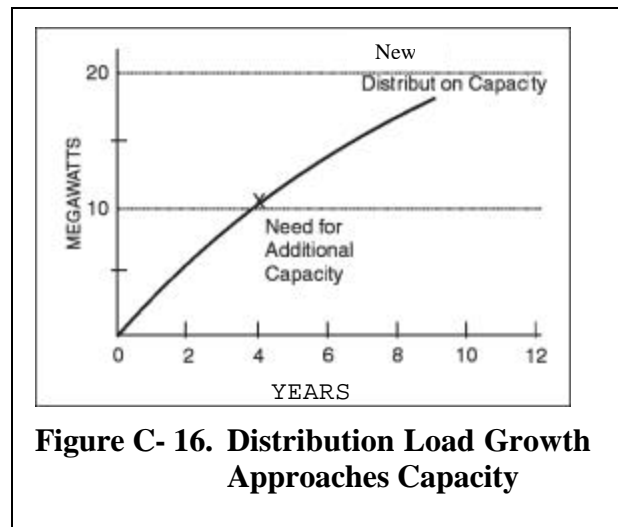
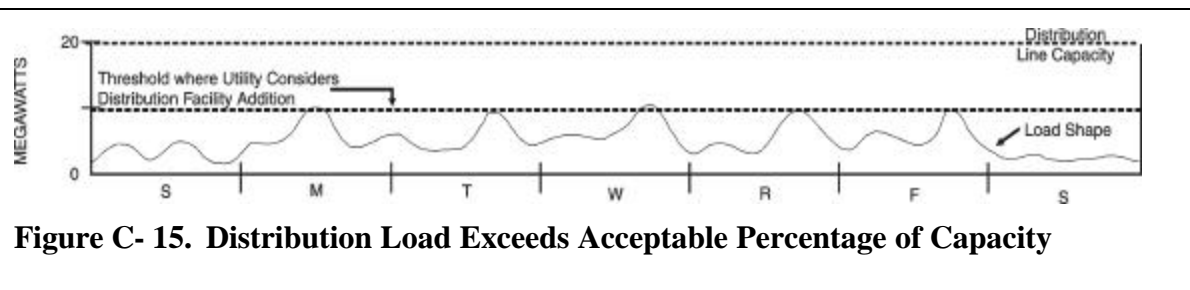


Figure C- 14. Storage Response to Increase Transmission Capacity Until New Facilities are Cost-justified

Distribution Facility Deferral

As load demand approaches the capacity of distribution facilities, utilities add new lines and transformers. Figure C-15 shows a distribution load that allows an insufficient margin between its peaks and the system capacity. Figure C-16 illustrates demand growth that approaches the installed distribution capacity. Because demand will continue to grow, utilities install facilities that exceed existing load demands. Therefore, utilities under-utilize expensive distribution facilities during their first several years in service. With energy storage systems, utilities can meet current load demands with existing distribution facilities, and defer the purchase and installation until the demand better justifies new facilities.

An energy storage system to defer installation of new distribution capacity requires power on the order of 10s of kW to a few MW, and must provide 1 to 3 hours of storage. In a typical distribution facility, the battery system would operate most frequently during daily high-load periods that occur during seasonal peaks. Figure C-17 shows the energy storage discharging to meet demand.



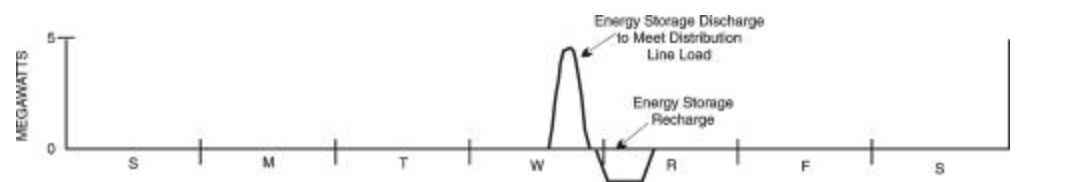
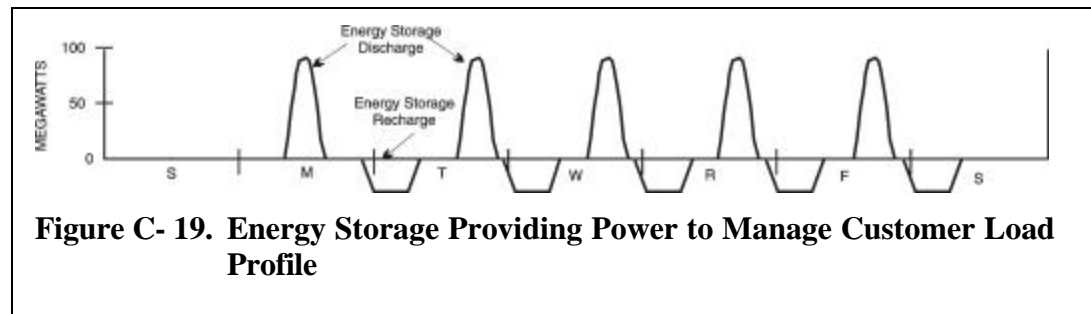
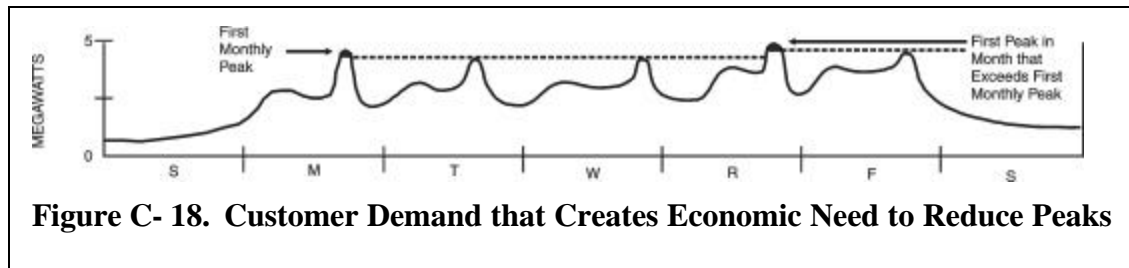


Figure C- 17. Storage Provides Peak Power to Temporarily Defer Purchase of New Equipment Until it is Cost-justified

Customer Energy Management

Utilities typically charge commercial and industrial customers a monthly fee (peak-demand charge) based on the highest power drawn during the month. By reducing peak demand or by “peak shaving,” customers can significantly reduce peak demand charges. Figure C-18 illustrates the way that customers typically reduce monthly demand peaks. At the beginning of the month, the energy storage system shaves the first peak and notes the reduced peak power level. Then the energy storage system remains idle until power demand exceeds the reference value noted during the previous peak shaving event. When load exceeds the reference value, the system discharges the battery to shave this peak, and again notes the maximum power that the utility provided to the customer. This process continues until the end of the month, when the system resets.

In Figure C-18, peak shaving occurs twice to the customer’s load during the first week in a billing period. The energy management system shaves the first monthly peak, stores the maximum load value (represented by the lowest dashed line) and waits for load to exceed the stored value to operate a second time. Figure C-19 shows the energy storage operation with discharge for peak shaving and recharge during off-peak hours. In this application, the energy storage system would discharge seven or eight times per month, or about 100 times per year. The system size would be in the 10 kW to 1 MW range. The energy storage system would need one to two hours of storage capacity.



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Renewable Energy Management

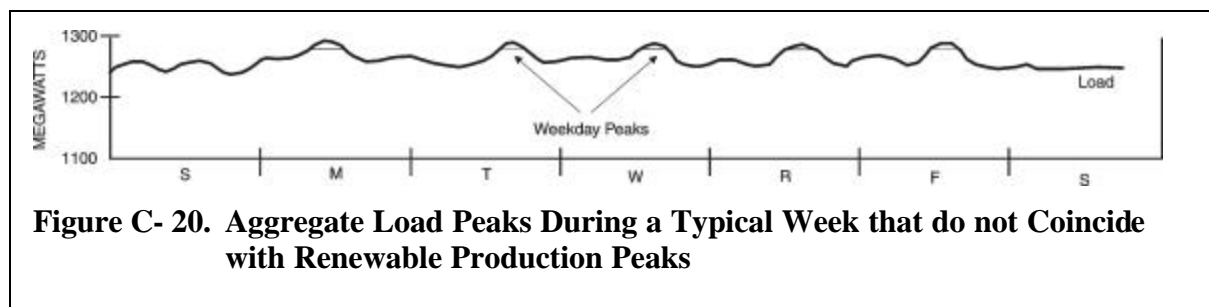
Energy storage systems have several potential applications for renewable systems. In one near-term application, a storage system can help to deliver renewable energy when it is most needed. By storing power from renewable energy systems that produce power at times that do not coincide with the utility system demand peak, the owner of the renewable resource can deliver power at peak times, and create “coincident peaks” between utility demand and the renewables supply. Because utilities will pay a higher rate for renewable energy delivered on peak, renewable power delivered during the utility peak has greater economic value. The “value” of the electricity produced by renewables will be a growing driver in our nation’s inclusion of green resources in the generation mix.

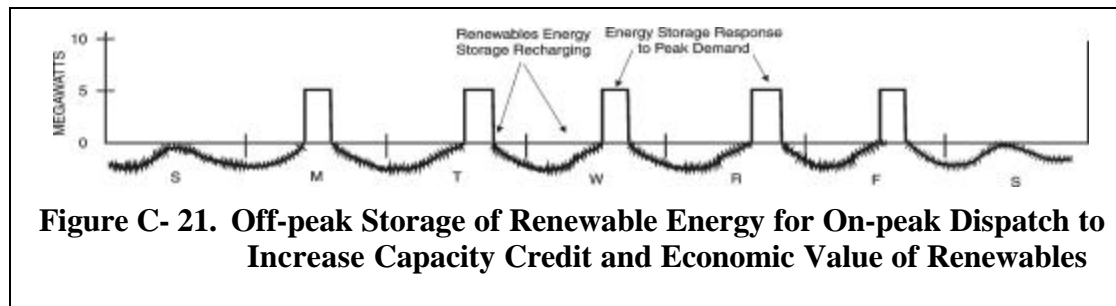
Another near-term renewable system application for energy storage takes energy from a source with variable power and delivers reliable, constant power on demand. Because utilities must guarantee the amount of power that they have available, such power “firming” makes variable renewable sources more viable, and adds to their economic value.

The storage system for either application would need to provide from 10 kW to 100 MW. The storage system would need storage capacity in the fractions of seconds to address transient fluctuations and one to ten hours for diurnal storage or coincident peaking. For coincident peaking, the storage system would discharge about 250 times per year, during weekday utility peaks. For power firming, the storage system would charge and discharge randomly, as renewable sources wax and wane.

In the long term, a utility with a significant percentage of renewable power may require storage capacity of days to weeks to ride through periods with cloudy skies or windless days. However, this application is still on the horizon of energy storage development.

Figure C-20 shows the utility load shape with daily peaks in the afternoon and early evening. Figure C-21 shows the storage response to make energy available coincident with demand peaks.





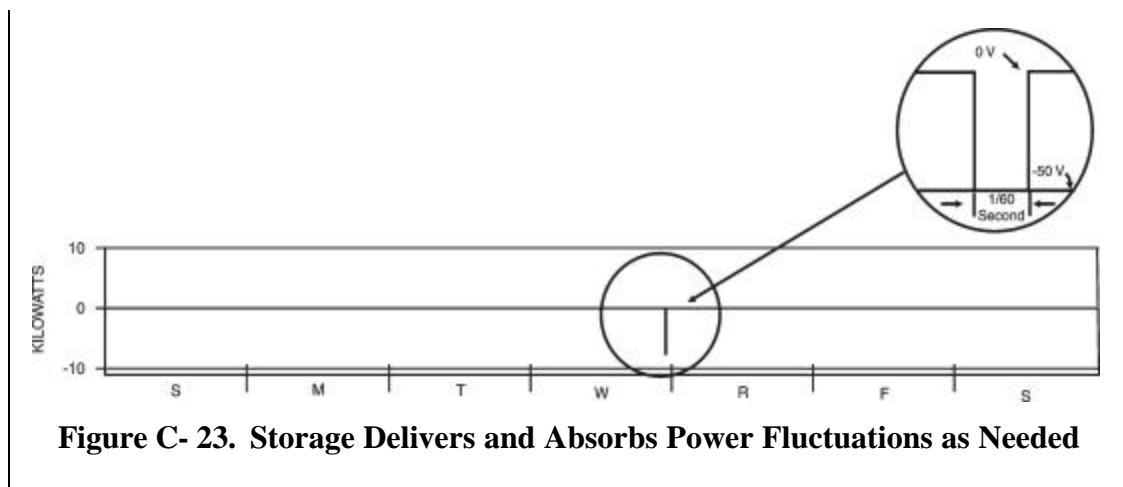
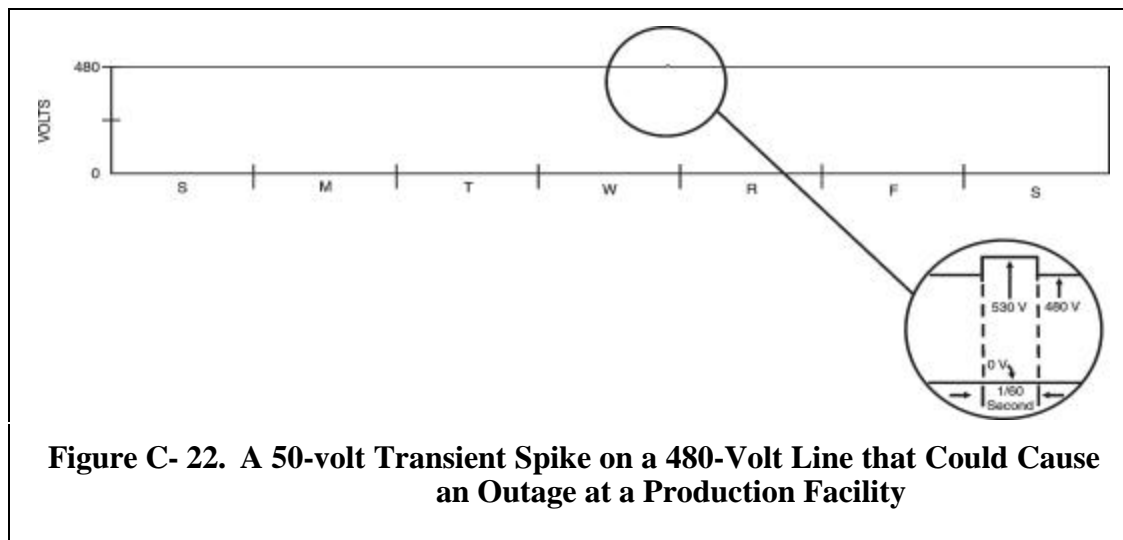
Power Quality and Reliability

Small industrial and commercial customers often operate sensitive electronic systems that cannot tolerate voltage sags, spikes, or loss of power. The duration of a power sag may be only one or two cycles ($1/60^{\text{th}}$ of a second) but the effects can be costly. Microprocessors on assembly lines may shut down, and production and data processing suffer. Figure C-22 illustrates a momentary voltage spike that might cause such production loss.

To protect these electronic devices, customers can install energy storage systems to prevent power sags, spikes, and failures from ever reaching their equipment. If an energy storage system operates in parallel with the load, the battery system disconnects load from a faulted power supply, and provides power until normal utility voltage returns. If an energy system operates in series with the load, the power conversion system always operates. However, energy storage provides power only when voltage sags and interruptions occur. The energy storage system would require 100s of kilowatts and 15 minutes of storage.

Voltage sags, spikes, and power loss typically occur about 10 times a year. A self-commutated converter is necessary to reform 60-Hz voltage.

Figure C-23 shows a storage system installed in parallel with the load where it operates all of the time and provides or absorbs backup power as needed.



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Appendix D. Revisions to the Phase-I Cost-Breakdown Structure

The cost breakdown structure presented in the Phase I report considered battery energy storage systems only. A revised structure must consider additional subsystems that are part of electromechanical and electrical storage systems. However, the treatment must be comparable to the costing structure for traditional technologies. Table D-1 presents a slightly revised version of the Phase I structure as a tool for future analysis to develop a more refined cost estimate. The text after the table discusses other considerations that should be part of that refinement.

Some cost groups collapse into a line-item for turn-key systems. However, the detailed breakdown is necessary for specifying the system on which vendors bid. Additional detail will be necessary to allow true comparative costing of systems. As noted in Section 4 of this report, realistic cost comparisons must also consider the complete life-time cost of a system. This issue is especially relevant for components of the systems that may be considered hazardous materials that must be disposed of at a Resource Conservation Recovery Act (RCRA) permitted facility (sodium, sulfur, bromine, lead, sulfuric acid, sodium polysulfide, chromium used to coat Na/S containers for corrosion protection, etc.).

While many system manufacturers are offering reclamation and recycling of the spent storage media, and the customer for the system will not directly bear the cost, it is a part of the system cost and should be considered for direct comparison. For any system, demolition permits, labor, and material disposal (including landfill permits, portage and tipping fees) will be important decommissioning costs.

Table D-1. Cost Components for an Energy Storage System

Storage Device	<ol style="list-style-type: none"> 1. Electrochemical storage device 2. Electromechanical storage device 3. Electrical storage device
Interfaces to AC Load and Source	<ol style="list-style-type: none"> 1. New lines to serve installation 2. Transformer between utility voltage and battery system AC voltage 3. Protection devices (e.g., switches, breakers, fuses)
Power Conversion System¹	<ol style="list-style-type: none"> 1. AC switchgear/disconnect 2. Rectifier/inverter 3. DC switchgear/disconnect 4. Protection devices (e.g., switches, breakers, fuses)
Auxiliary Systems and Accessories	<ol style="list-style-type: none"> 1. Electrical: interconnects, protection devices (e.g., switches, breakers, fuses), chargers 2. Mechanical: racking/physical support, watering/heating/air and fluid pumping systems, safety equipment (e.g., ventilation, fire equipment, detectors, respirators, spill troughs), cryogenic refrigeration, vacuum system
Monitors & Controls¹	<ol style="list-style-type: none"> 1. Monitors/diagnostics: storage media, power conversion, subsystems (bearings, cryogenics, vacuum) 2. Controls: storage media, protection devices, power conversion, subsystems (bearings, cryogenics, vacuum)
Facilities¹	<ol style="list-style-type: none"> 1. Foundation and structure 2. Materials 3. Lighting/plumbing 4. Access road and landscaping 5. Grounding/cabling 6. Heating, ventilation, air conditioning (HVAC)
Labor Costs	<ol style="list-style-type: none"> 1. Construction 2. Installation and start-up testing 3. Operations 4. Occupational Safety and Health Association (OSHA) reporting
Financing	<ol style="list-style-type: none"> 1. Finance initiation 2. Interest
Transportation¹	<ol style="list-style-type: none"> 1. Carrier charges 2. Permits
Taxes	<ol style="list-style-type: none"> 1. Sales tax on system 2. Income tax on revenues from use of system
Services	<ol style="list-style-type: none"> 1. Project management 2. Power quality and stability studies (e.g., relays, harmonic filters) 3. Permits for siting and operation
Operation and Maintenance	<ol style="list-style-type: none"> 1. Service contract: inspection, service costs, component replacement 2. Training for operation and maintenance workers 3. Monitoring/data acquisition²

¹ For turn-key systems, separate costing of these items may not be necessary because they will be incorporated in the vendors' prices.

² Data acquisition is optional, but has been proven to be of great value in subsequent decision-making.

Appendix E. Resources for Revision of Markets and Benefits Estimates

For utilities to consider energy storage as a viable commercial resource option, they must be able to quantify its benefits and costs. For manufacturers to invest in developing storage for utility applications, they must be reasonably certain of the potential market and its production demands and profits. In the Phase I Opportunities Analysis, participants estimated the use of storage in various applications and analysts used those estimates to project the potential market for storage and the magnitude of the benefits to the nation that could result from the use of storage in those applications.

At the outset of the Phase II Opportunities Analysis, participants hoped to refine those initial estimates and to make the estimates specific to the new applications definitions derived in the Phase II work. The original plan for the Phase II analysis was to hold three meetings, the first to define applications and their requirements, the second to identify which technologies could serve the applications and the third to gather data that would permit refined estimates of the markets and benefits. In the course of the first and second meetings, participants began to recognize that the information required to improve upon the Phase I estimates would require effort outside of the scope of the Phase II resources. Therefore, the ESS Program elected to address in the estimation of markets and benefits in a separate project.

Chapter 7 of the Phase I report details the analytic methods used in the first market/benefit projections for storage. The description of the analytic methods cites the studies and reports upon which data were drawn and assumptions made. The following list identifies studies from the Phase I report (and/or revisions and updates to those studies) that might be useful in future estimates of market and benefits of energy storage.

1. SAND93-3900, "Battery Energy Storage: A Preliminary Assessment of National Benefits (The Gateway Study)." – this report was the first attempt to estimate the potential benefits of using energy storage in the US electric power grid.
2. "Benefits of Battery Storage as Spinning Reserve, EPRI-AP-5327," Zaininger – this report, conducted for electric utility customers by

ZECO of California, identified that ensuring emergency reserve power represents about 0.4 percent of utilities' operating expenses. This number may change with deregulation and competition.

3. "Financial Statistics for Investor-Owned Electric Utilities, DOE/EIA-0437" – this report shows that national utility production costs were \$70 billion in 1990. This number allows estimation of the cost of providing rapid reserve in the nation when taken with the 0.4 percent estimate given by the previous report.
4. "DOE/EIA Annual Energy Outlook 2000," – the data available in this document is useful for 1) Estimating the amount of renewable resources in the US generation mix and the potential market and benefits from using storage to increase renewables penetration and capacity factor; (Table A17) 2) Projecting generation capacity for the US that, when taken with the data from Reference 7, allow estimation of the potential for deferring transmission capacity installations; and 3) Estimating benefits from energy storage in customer energy management applications.
5. "Photovoltaic Industry Survey: An Evaluation of the Photovoltaic Battery Market, 1992," Document Number 93-101-RES, The Photovoltaic Design Assistance Center at SNL – the results of this survey will help refine estimates of benefits and develop market projects for energy storage system support of photovoltaics.
6. "Integration of Renewable Energy Sources into Electric Power Distribution Systems, Vol.2, Utility Case Assessments, ORNL-6775/2," – this report estimates that capacitors cost between \$10 and \$120 per kVAR, figures useful to analysis of energy storage in renewable support. The cost of capacitors is also useful in analysis of secondary benefits of installed storage system such as capacity factor correction. It also cites the installed costs of 25 MVA transformers at \$1M, or more, a figure useful in the estimation of the benefits of renewables support and distribution capacity deferral.
7. "Staff Report on Electric Power Supply and Demand for the Contiguous United States (1989-1998)" DOE/IE-0018 – this report details the number of miles of transmission lines (above 22 kV) installed for every MW of new generation capacity and estimates installations of

extra-high voltage (EHV) transmission lines (254 kV and above). This data will help in estimating transmission capacity deferral benefits.

8. “Potential Benefits of Battery Storage to Electrical Transmission and Distribution Systems, EPRI GS6681,”- this document cites that transmission lines cost about \$1 million per mile, excluding transformers, relays, or other auxiliaries to the cable and its supports. This data with the data from References 4 and 7 allow estimation of the benefits from transmission and distribution capacity deferral.
9. “Load-Leveling Lead-Acid Battery Systems for Customer-Side Applications, Market Potential and Commercialization Strategy, EPRI-AP/EM-5895” – this report cites that a typical demand charge for a large customer is near \$12/kW. This figure is useful in estimating benefits from energy storage in Customer Energy Management applications.
10. *Handbook of Batteries 2nd Edition*. D. Linden, ed. McGraw-Hill Book Company. New York. 1994

This list of resources is intended to assist future efforts to assess the markets and benefits of employing energy storage technologies in electric power applications defined in the main body of this report.

